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# **Application of CFD to Abrupt Wing Stall Using RANS and DES**

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**NASA LaRC SAMS Contract NAS1-00135**


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**Acknowledgements: Joe Chambers, Paresh Parikh,  
Scott Morton (USAF), ASC MSRC**


# Outline

- Motivation
- Grid
- Static cases
  - Solution procedure
  - Results
- Oscillating roll cases
  - Solution procedure
  - Results
- Conclusions

Previous work published at AIAA meeting in Reno 2003, and to be published in AIAA Journal of aircraft (FOM=Figure of Merit).



# Motivation?



- Pre-production F/A-18E
  - Exhibited “wing drop” in flight test
    - “wing drop” is an uncommanded lateral motion
    - “abrupt wing stall” is an aerodynamic characteristic, and can cause wing drop
  - Numerous flight tests resulting in a production fix
    - Revised flight control laws and porous wing fold fairing
  - A comprehensive program was created to be able to predict these phenomenon with wind tunnels and CFD
    - Free-to-roll wind tunnel test method
    - FOM’s for steady and unsteady (non-moving) CFD
- **Current work: Progress CFD to calculations of damping derivatives and free-to-roll for this flow by application to pre-production F/A-18E**

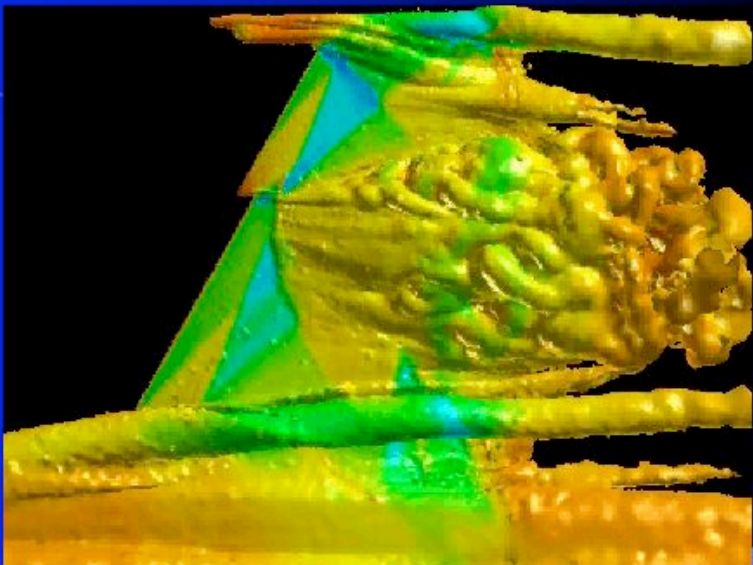
For DES, RANS is responsible for predicting boundary layer growth and separation. LES is responsible for predicting the geometry dependant turbulent flow features. Grid adaptation done using NASA Langley's RefineMesh program. Adaptation on time average of vorticity

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## Previous work (AIAA 03-0594)

- Goal was to use CFD to predict the unsteady shock oscillations seen in the experiments.
- RANS models failed to give unsteady results
- Detached-Eddy Simulation turbulence model
  - Hybrid RANS/LES
  - RANS in boundary layer
  - LES outside of boundary layer
- Solution based grid adaption

Iso of vorticity, colored by pressure,  $\alpha=9^\circ$



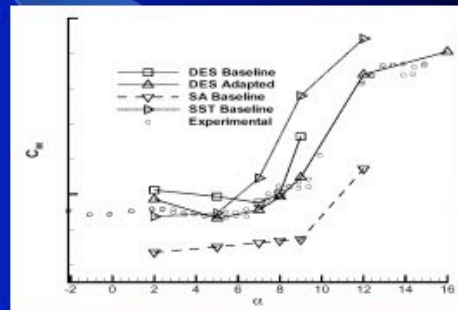
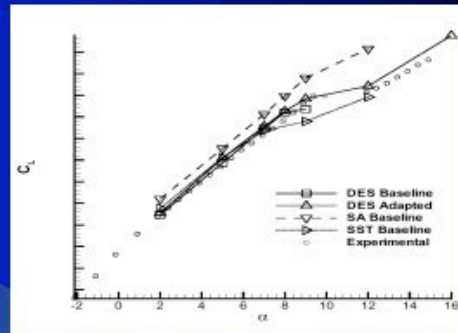


DES results are time-averaged coefficients. Left axis removed to protect proprietary data.

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## Previous work (AIAA 03-0594)

- 10/10/5 flap set with no tails
- SST predicted early lift curve break
- DES showed an improved lift curve break (but on a grid finer than the current grid)
- Motivates inclusion of DES in the current project, along with RANS

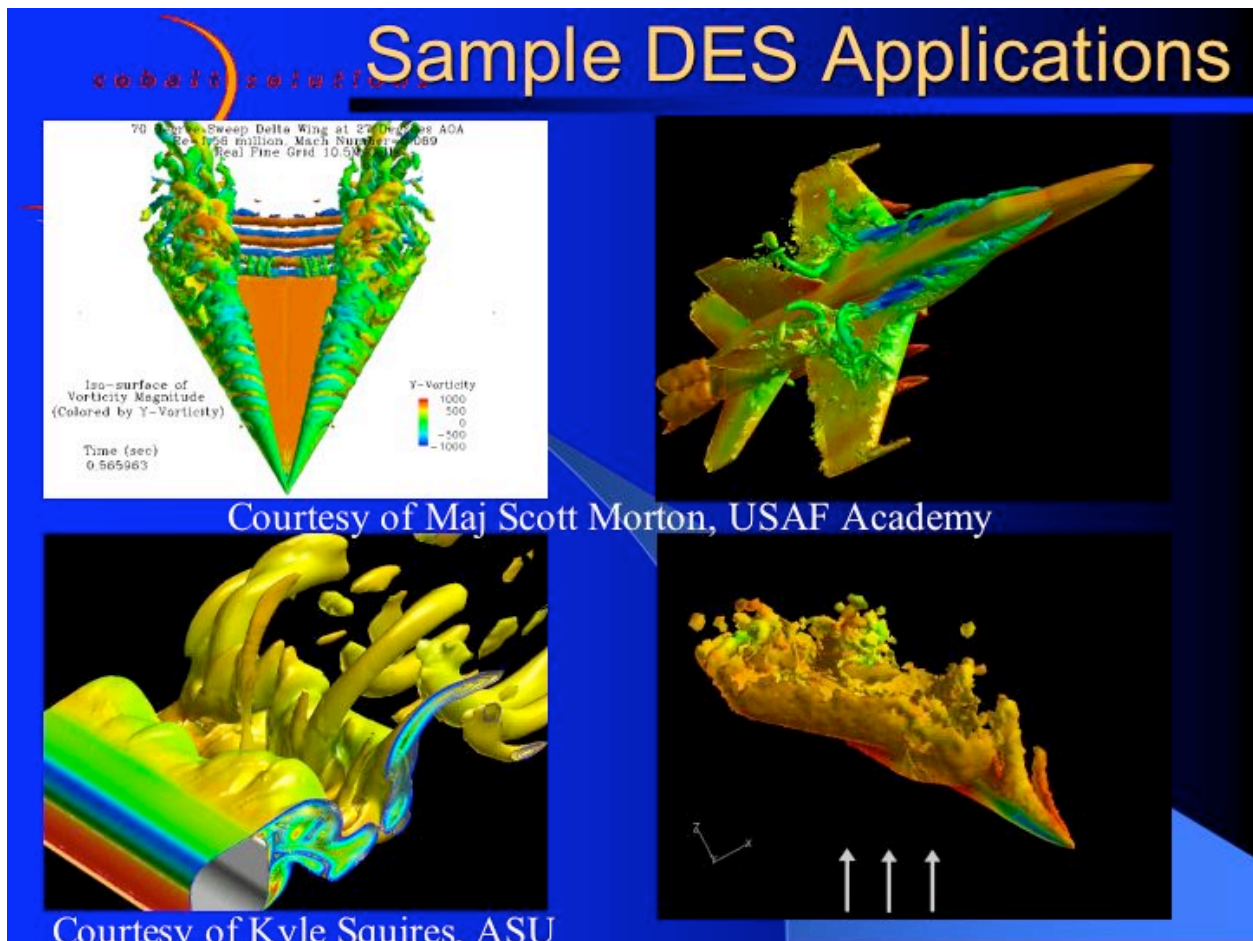


These DES projects represent a cross section of those done over the past few years using Cobalt.

Delta wing vortex breakdown on a delta wing and the F-18C done by Major Scott Morton of the USAF Academy (Scott.morton@usafa.af.mil).

2-D forebody geometry by Kyle Squires (squires@asu.edu).

Prescribed spin of the F-15E by James Forsythe.

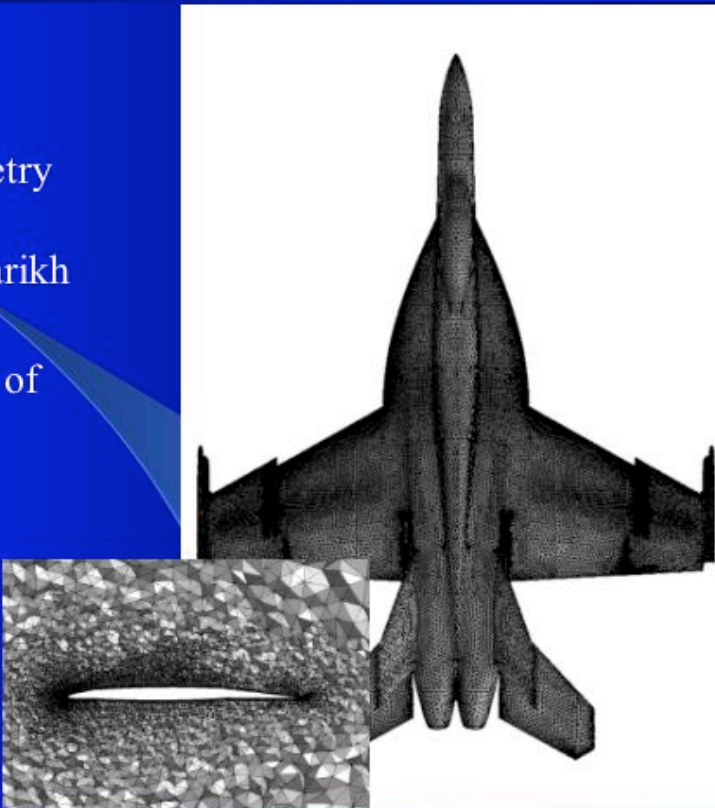


Prisms created using “Blacksmith” to recombine the tets in the boundary layer into prisms. Blacksmith is a Cobalt grid utility.

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## Grid


- Grid mirrored about symmetry plane
- Grid provided by Paresh Parikh
- 6/8/4 flap set
- $8.4 \times 10^6$  cells for both sides of aircraft
- Adaption performed on a  $9^\circ$  time-averaged DES solution under previous work
- Prisms in boundary layer
- Average  $y^+ < 0.7$

The image is a composite. The main part is a top-down view of a fighter jet, likely an F-22, with a dense, structured computational grid applied to its entire surface. The grid lines are visible as a fine mesh. In the bottom-left corner, there is a smaller, square inset showing a close-up, detailed view of the boundary layer mesh near a surface, highlighting the use of prisms to refine the grid near the wall.

The following are non-moving cases – but can be unsteady (for DES)



CPU hours based on a Compaq ES45. Timestep for DES non-dimensionalized by chord and freestream velocity.




## Solution Procedure

- Menter's SST RANS model
  - Convergence monitored by observing forces and moments. Rolling moment was generally the most sensitive and last to converge.
    - 4000 iterations
    - 1 Newton sub-iteration
    - CFL of  $1 \times 10^6$
    - 2000 cpu hours per run.
- Spalart-Allmaras based DES model
  - Unsteady flow simulation
    - 16000 iterations
    - 3 Newton sub-iterations
    - $\Delta t^* = 0.01$
    - 8x the cost of the steady RANS simulations



Model was set to a given pitch angle (theta), then rolled about the longitudinal axis (phi). This resulted in a decrease of alpha, and an increase in beta as phi increased. The CFD was performed at the given alphas and betas, which were corrected in the wind tunnel data for wall effects.



# Test Matrix

- Conditions chosen to match NASA Langley wind tunnel test 565
- Mach=0.9
- $Re_c = 3.9 \times 10^6$
- Flow through engines
- Sting not included in grid

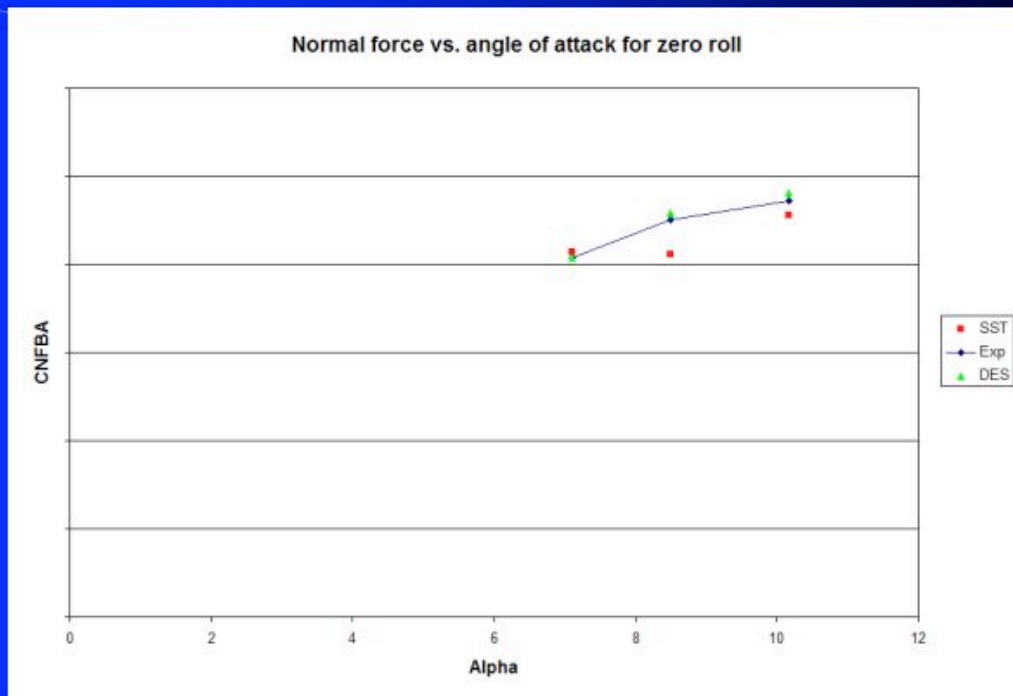
247			
ALPHA	BETA	PHI	THETA
7.11	-0.14	-0.13	7.01
7.03	0.86	9.87	6.97
6.32	2.73	29.75	6.74
4.03	4.89	59.78	6.14

240			
ALPHA	BETA	PHI	THETA
8.50	0.35	3.84	8.40
8.12	1.04	9.82	8.08
7.58	3.42	29.63	8.18

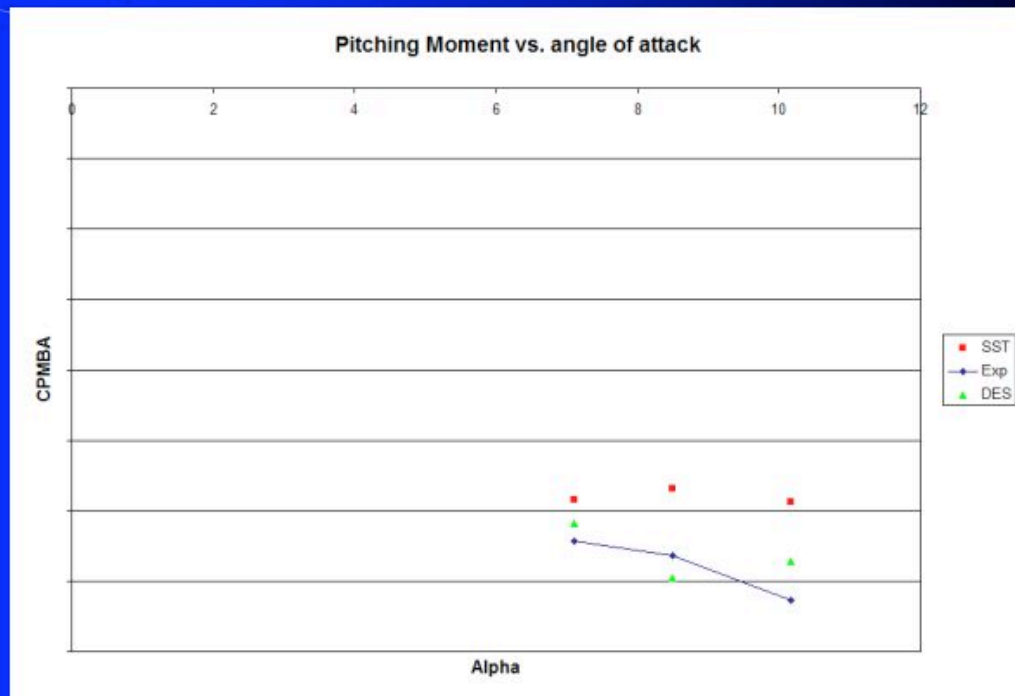
242			
ALPHA	BETA	PHI	THETA
9.04	1.17	9.69	9.00
8.20	3.74	29.56	8.87

244			
ALPHA	BETA	PHI	THETA
10.17	-0.12	-0.02	10.06
10.05	1.38	9.79	10.03
9.06	4.23	29.49	9.86
5.69	7.54	59.53	9.26

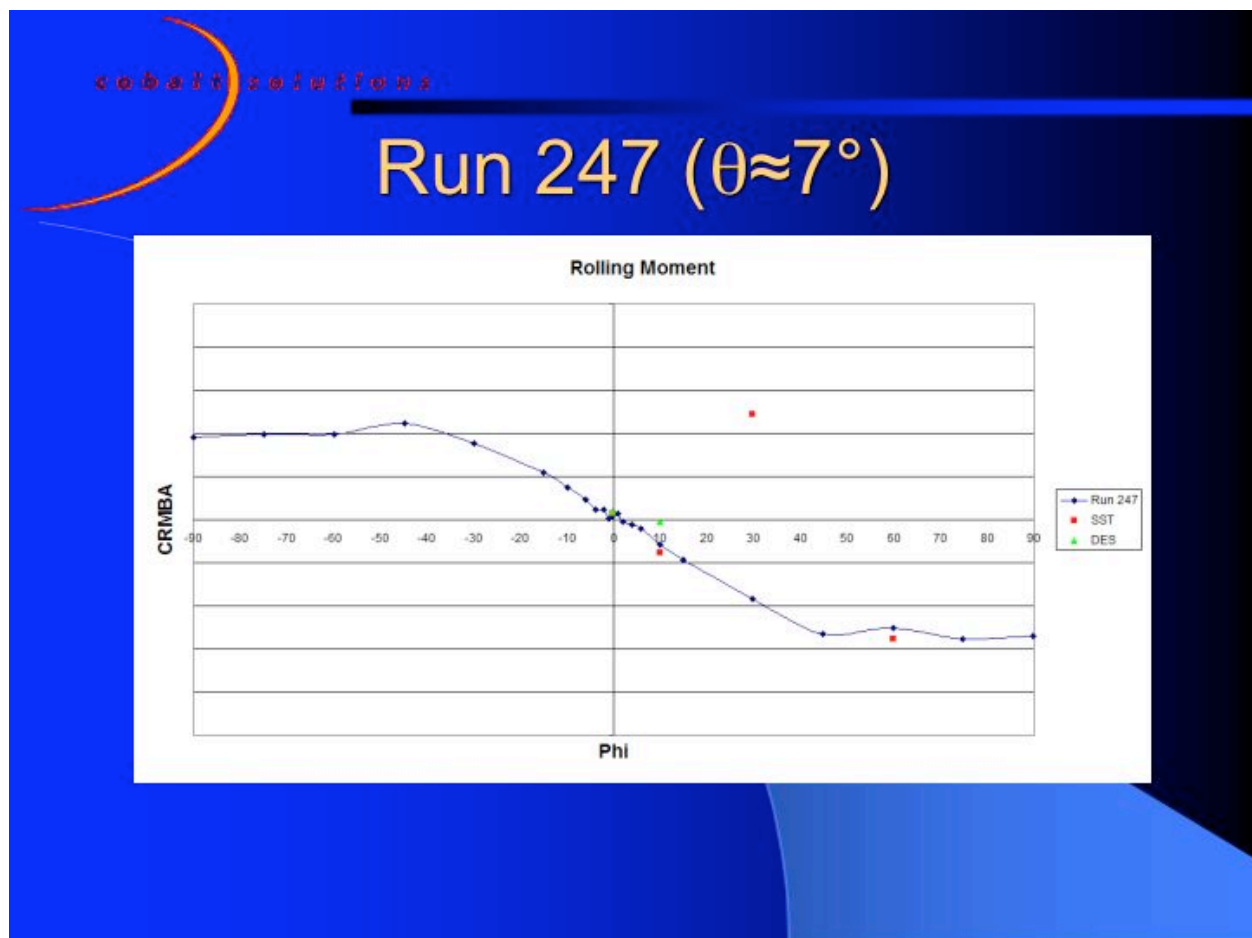
# Normal force for near-zero sideslip



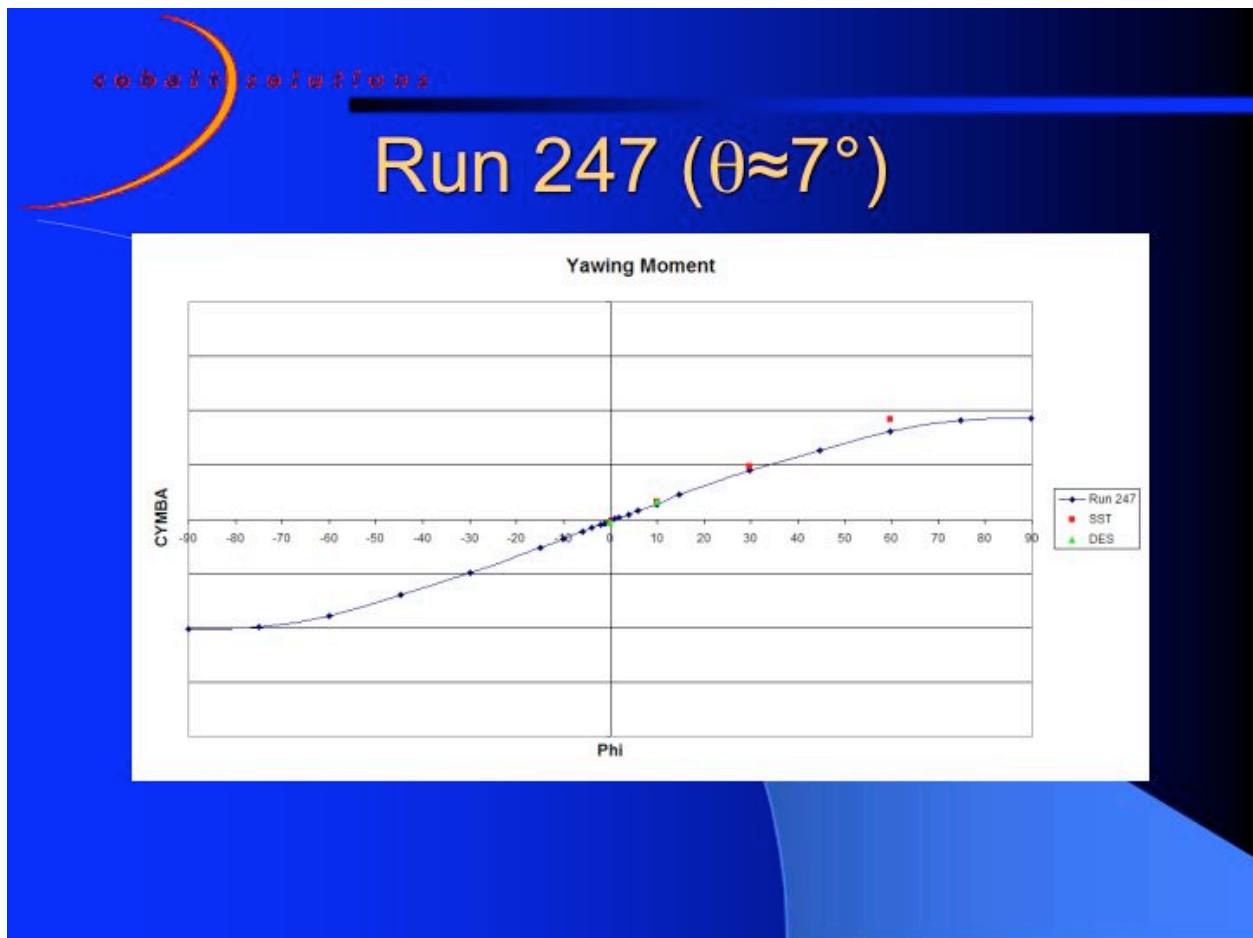
# Pitching moment for near-zero sideslip



Note reversal of rolling moment for  $\phi=30$  using SST.

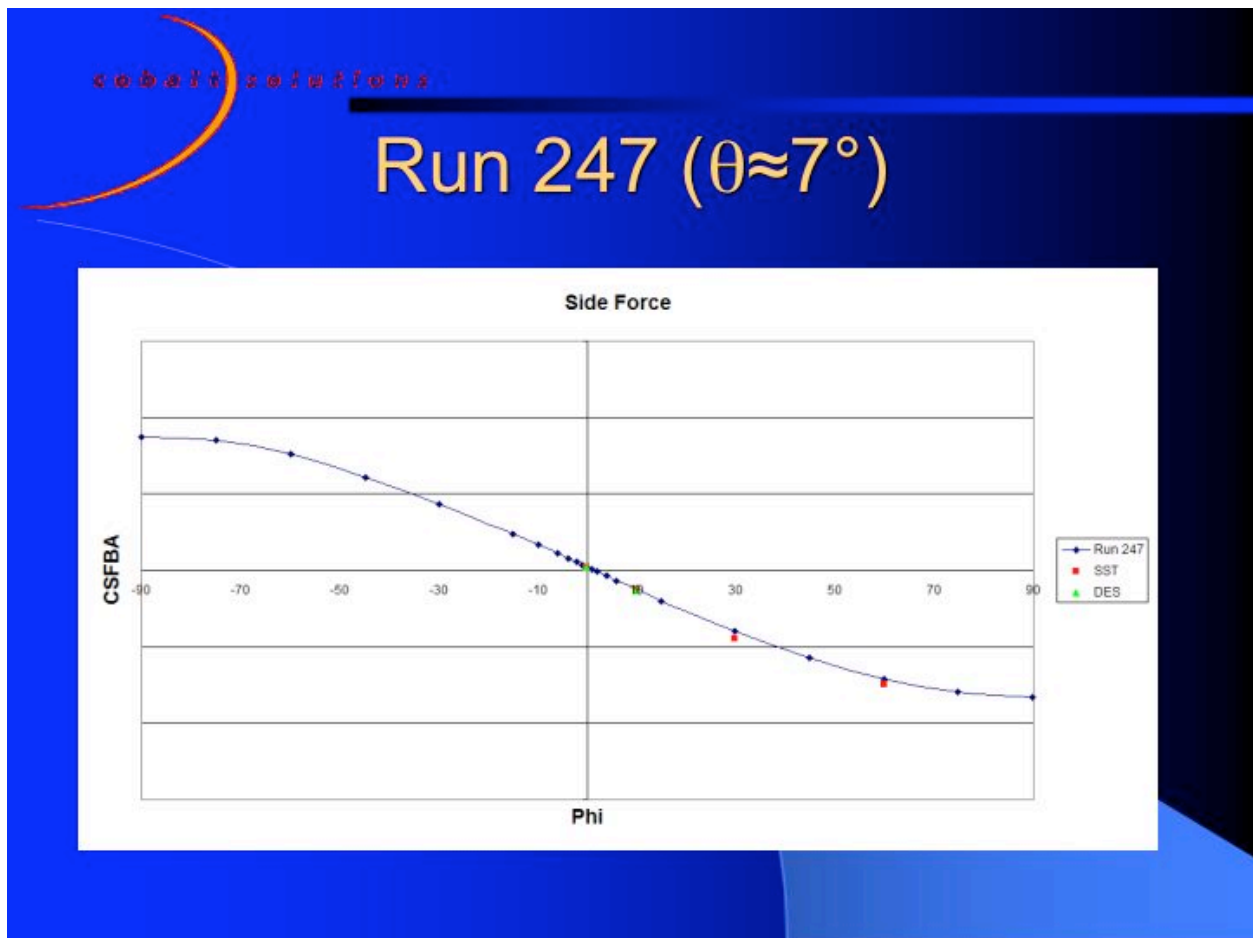


Yawing moment well predicted – as with all cases.

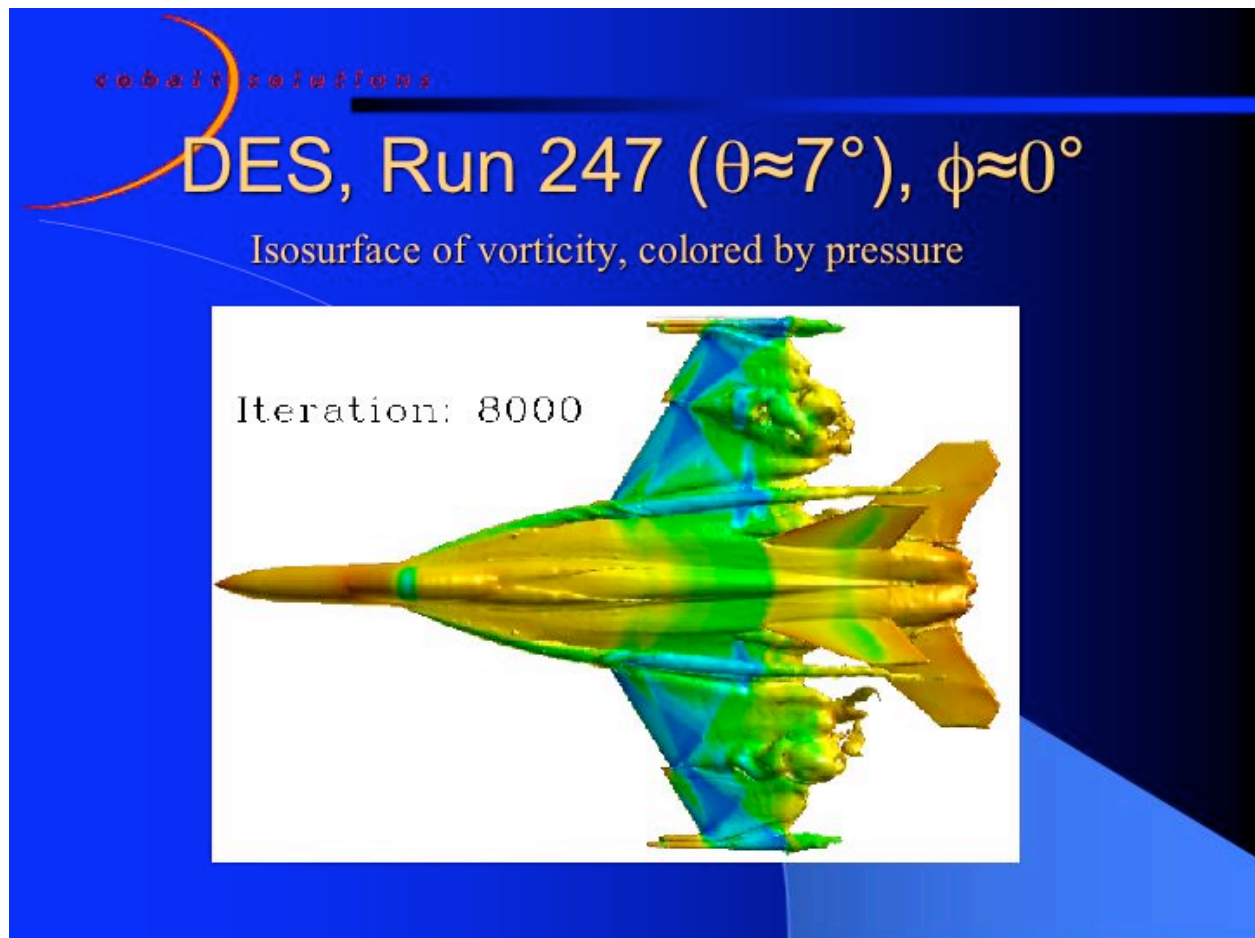




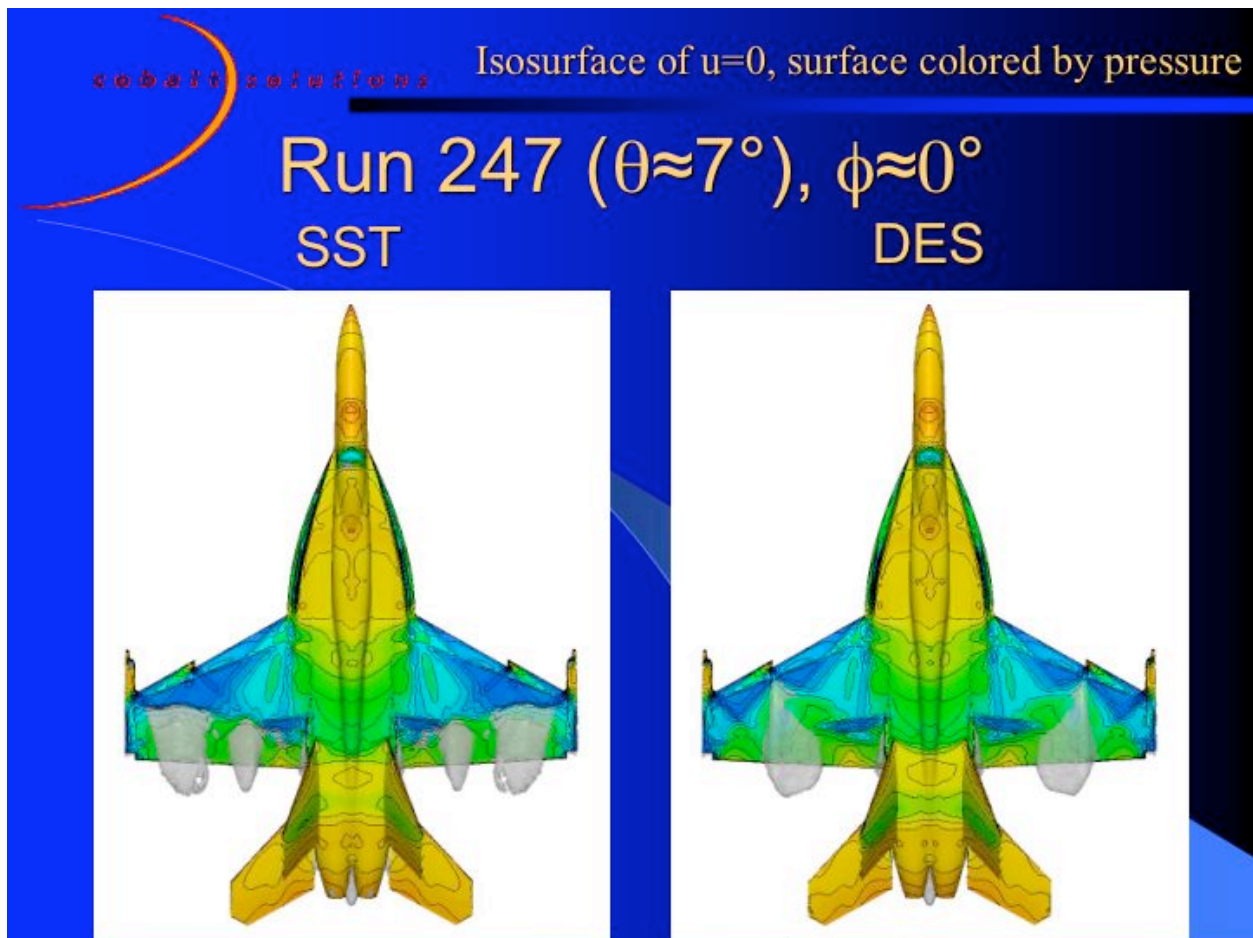
Side force well predicted – as with all cases.



Shock retreating off trailing edge of leading edge flap.



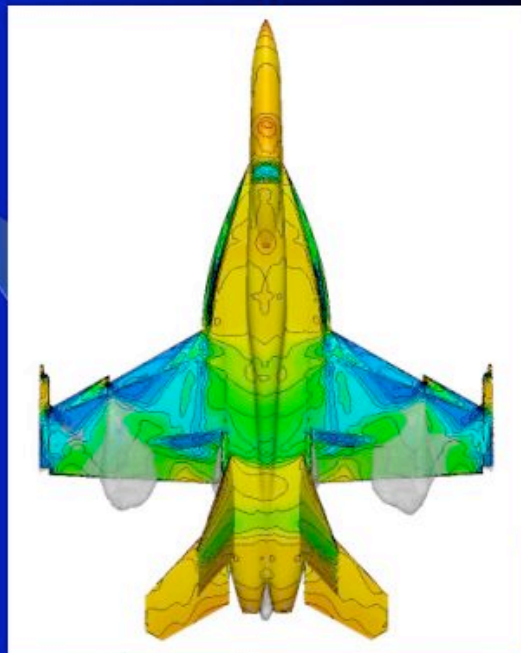
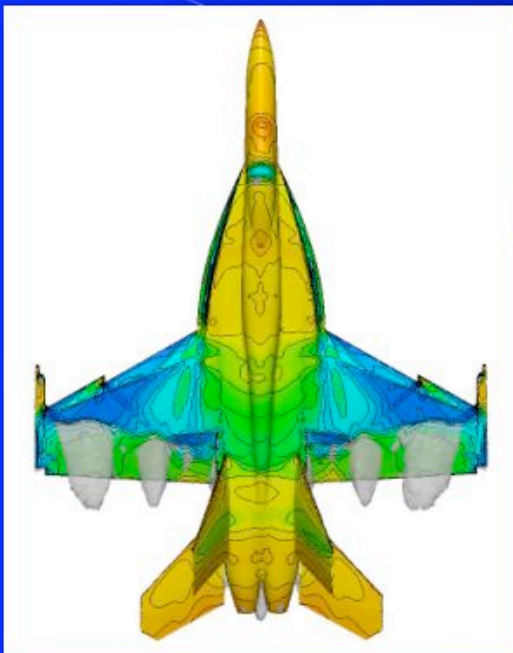
DES isosurface looks like separation is at trailing of leading edge flap. But it moves back from there unsteadily. This leads to the blue low pressure in the separation bubble (since it is not always separated).



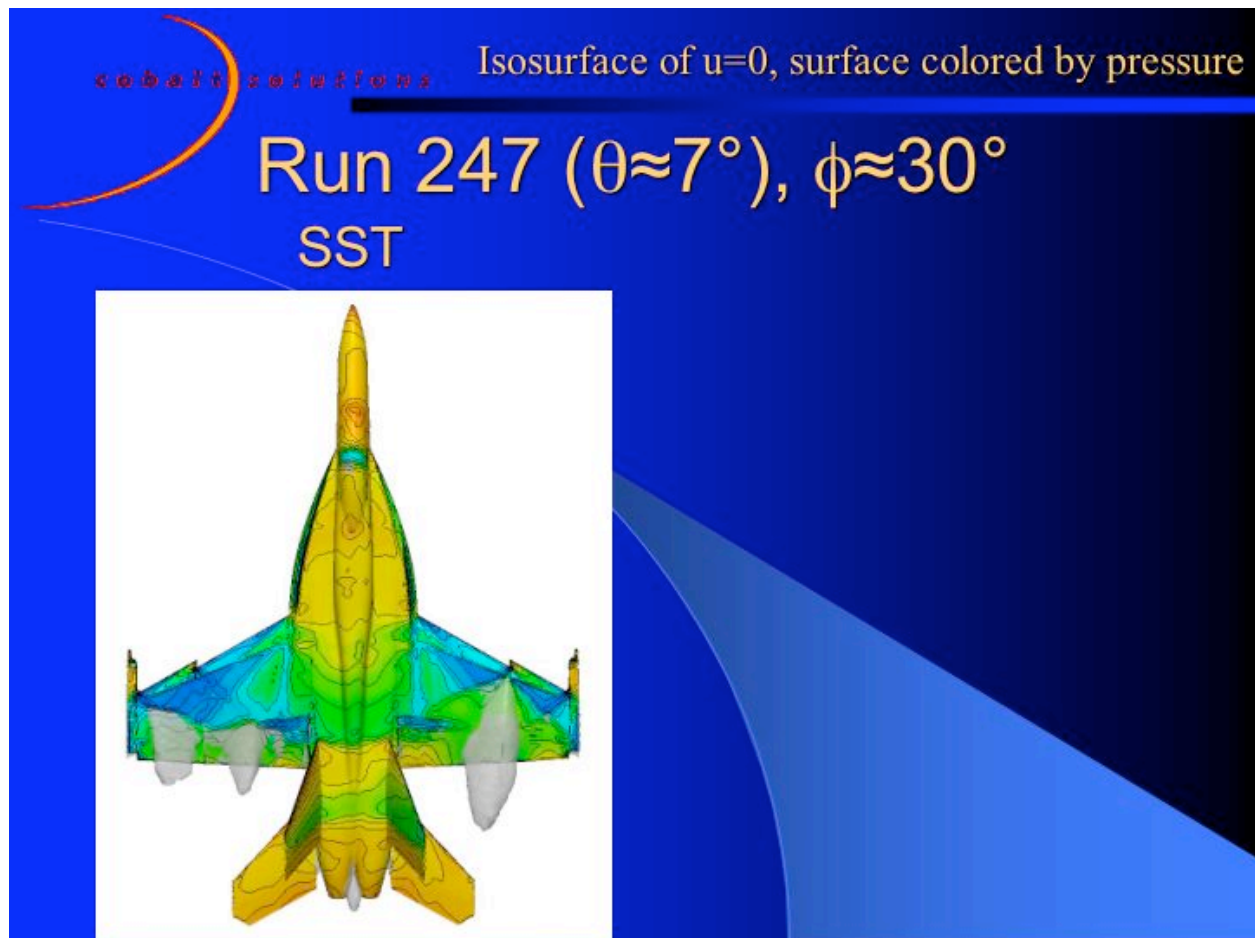
Run 247 ( $\theta \approx 7^\circ$ ),  $\phi \approx 10^\circ$

SST

DES

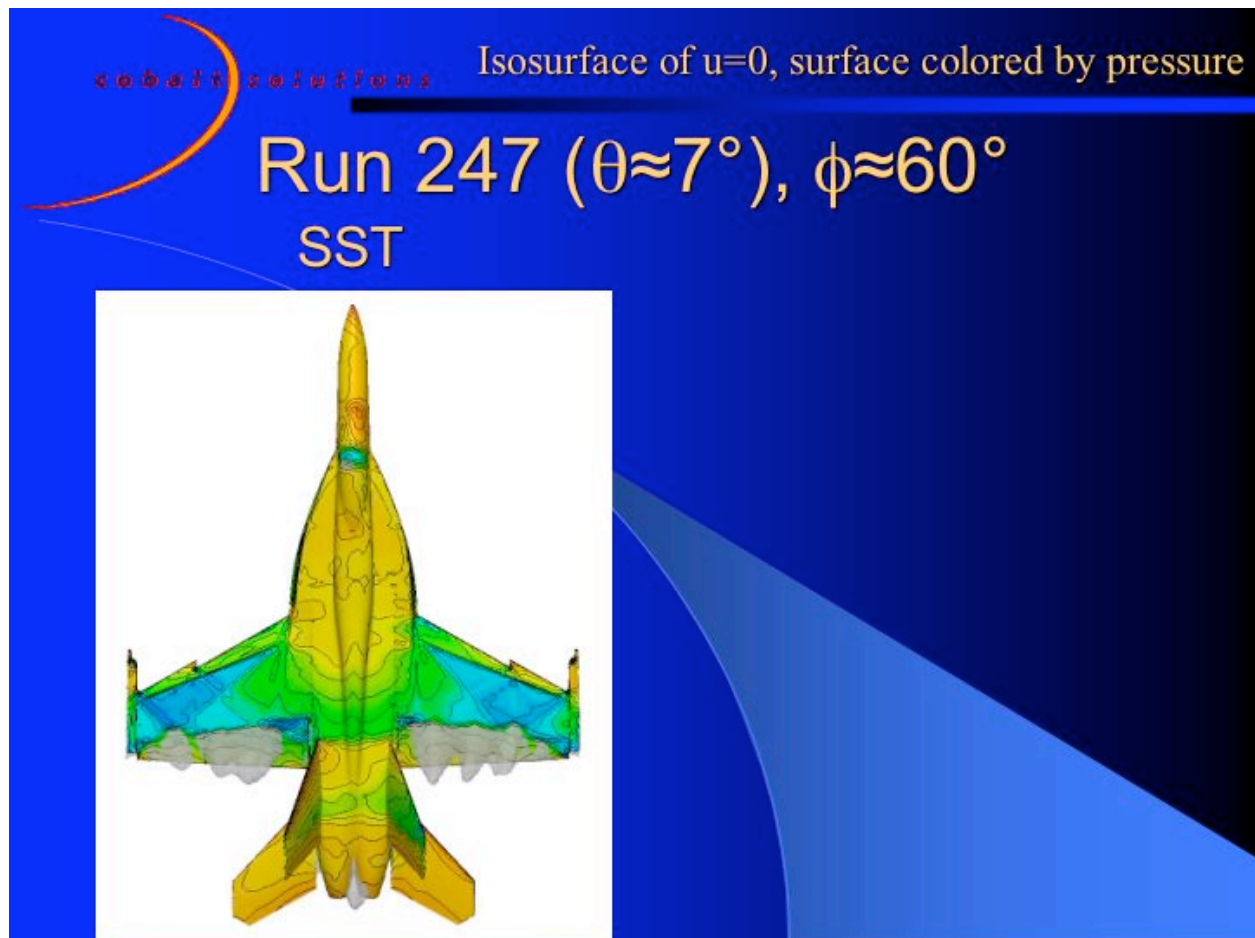


The separation moving forward on the right wing is the cause for the roll moment reversal.

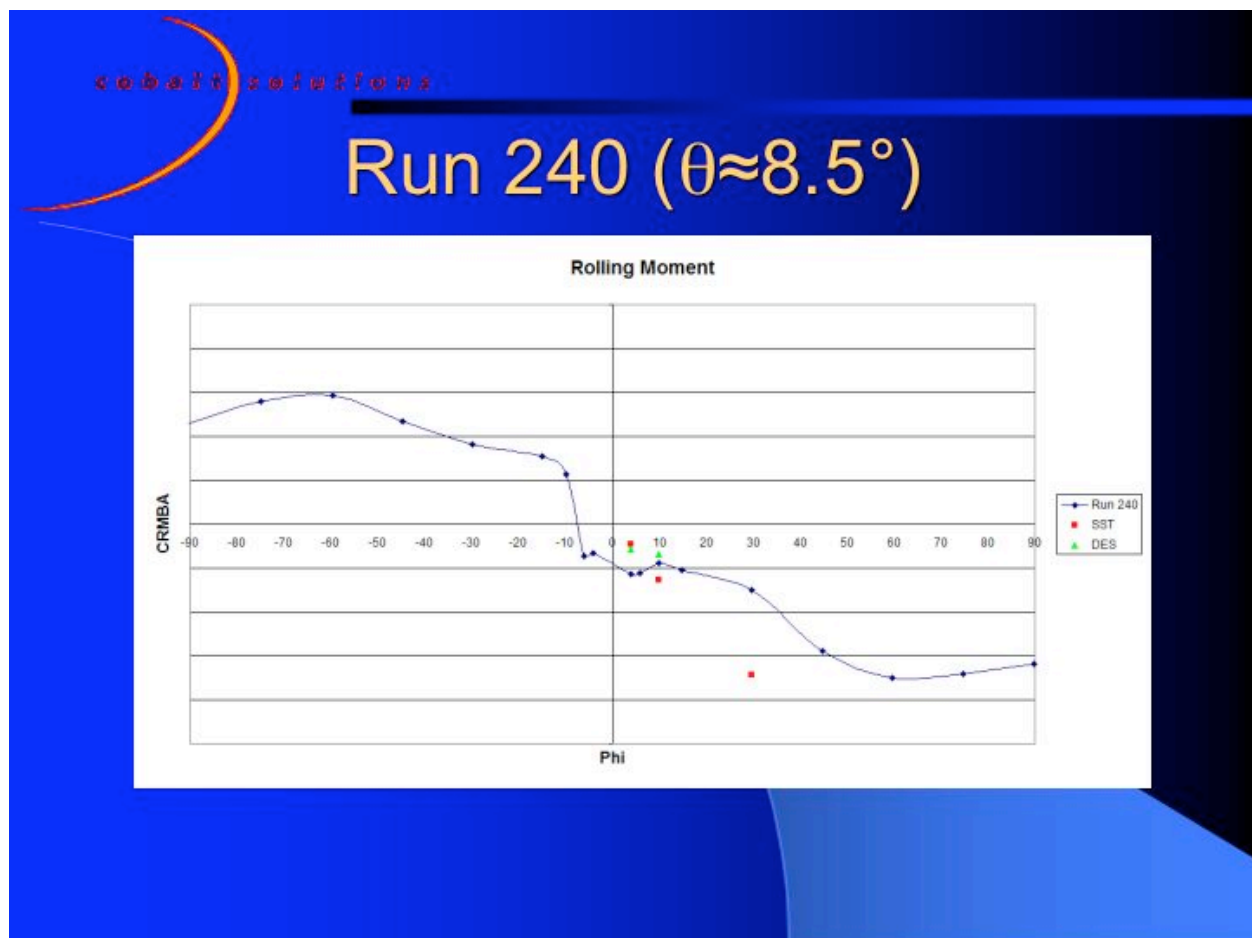




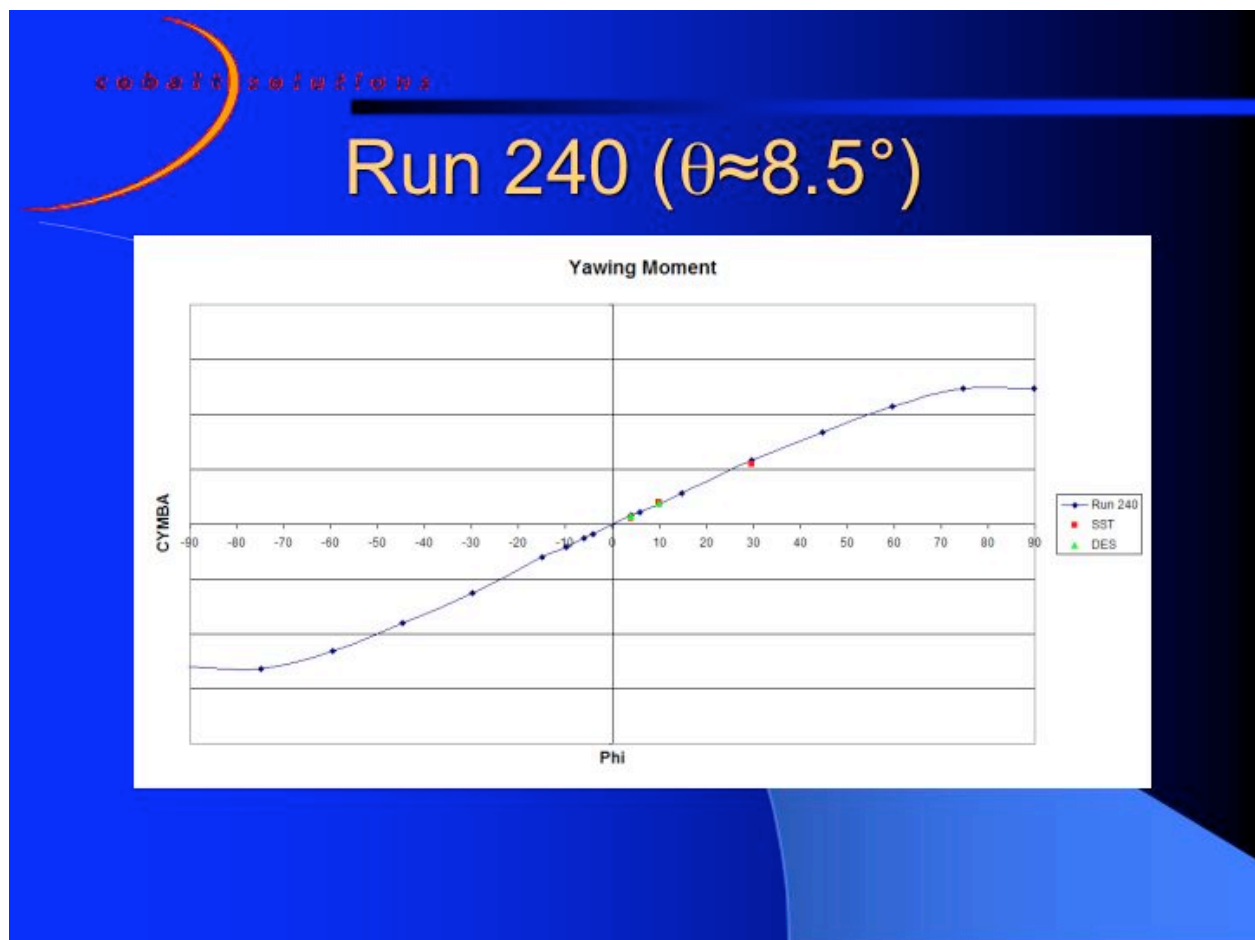
At this high  $\phi$ , the  $\alpha$  is reduced so much that the flow remains attached until the trailing edge of the wing.



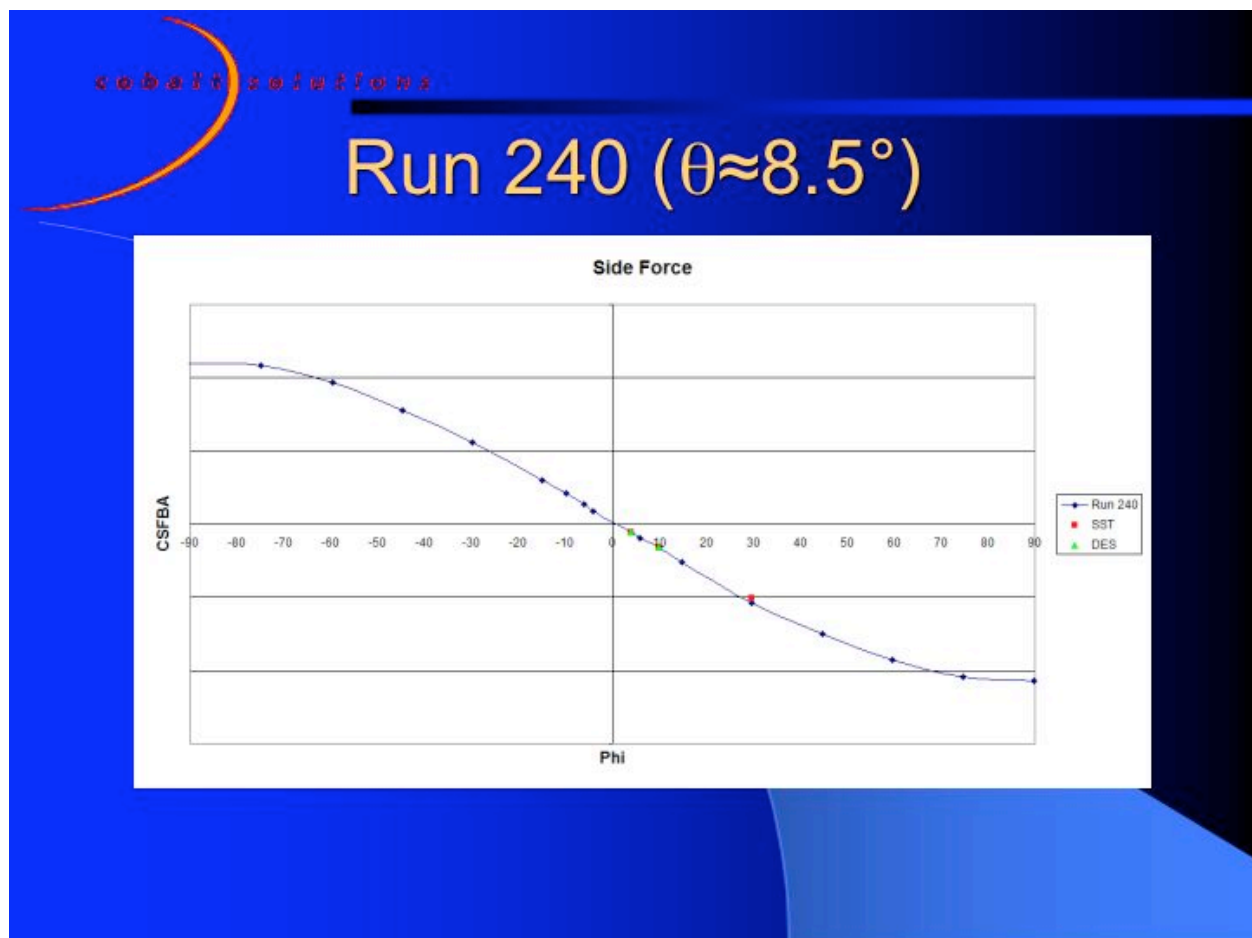
Note asymmetries in wind tunnel data. Decrease in lateral stability derivative picked up with DES.



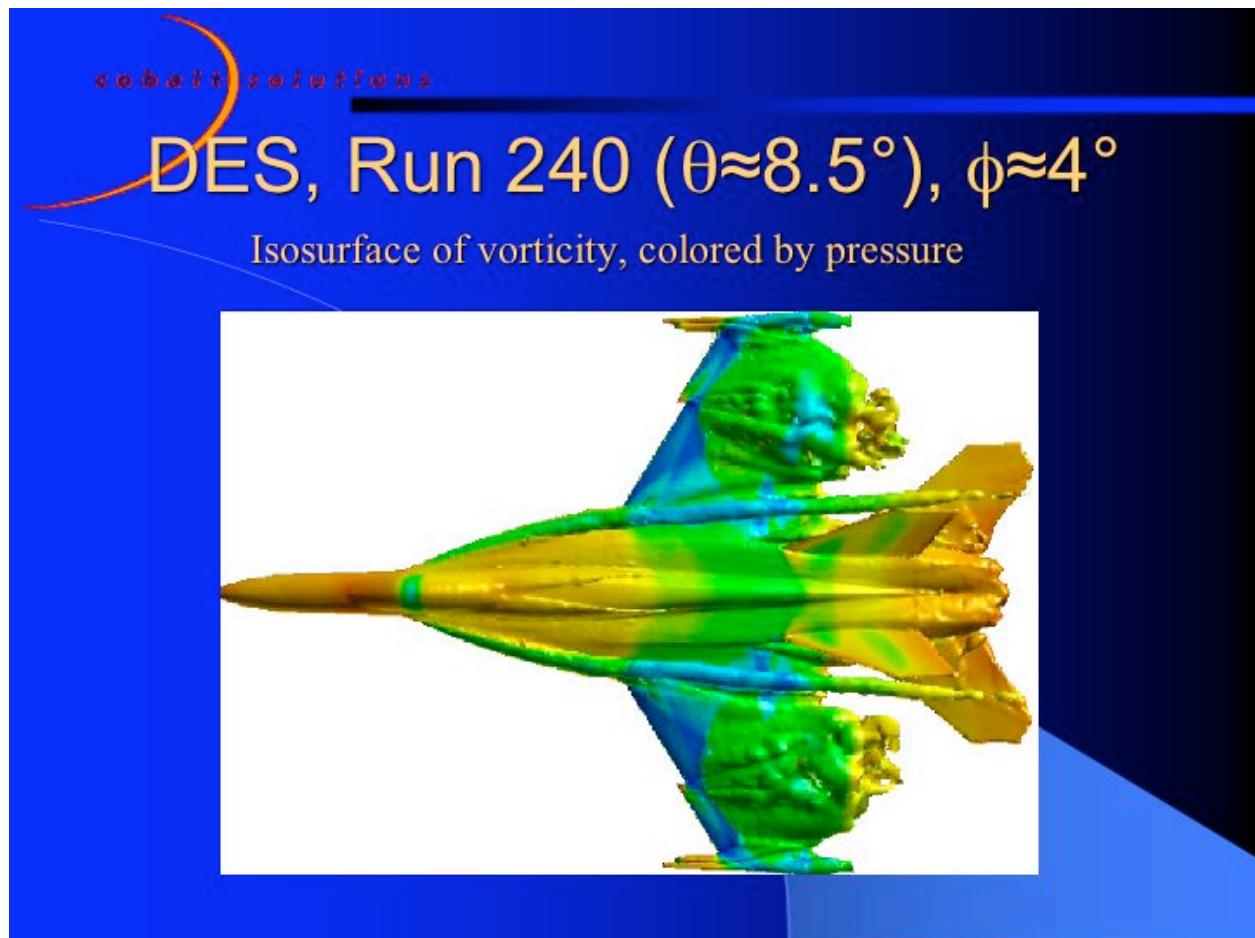
Good agreement for yawing moment, as with all cases – this is likely due to the attached flow at the tail, which is easily predicted.



Good agreement for side force, as with all cases – this is likely due to the attached flow at the tail, which is easily predicted.



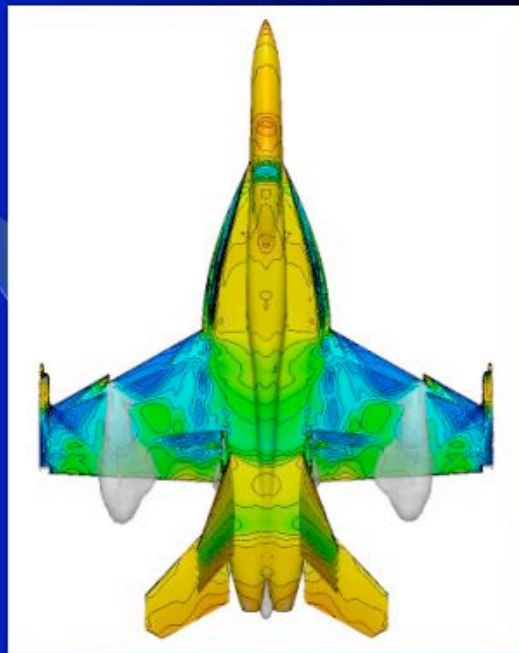
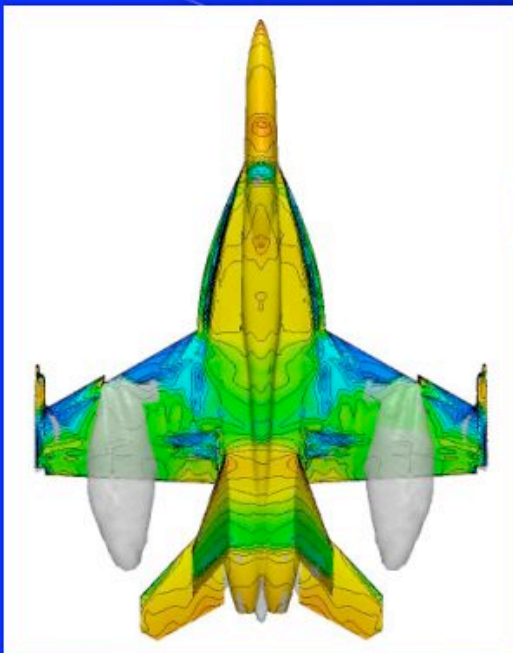
Separation is making it onto the leading edge of the leading edge flap.



Run 240 ( $\theta \approx 8.5^\circ$ ),  $\phi \approx 4^\circ$

SST

DES

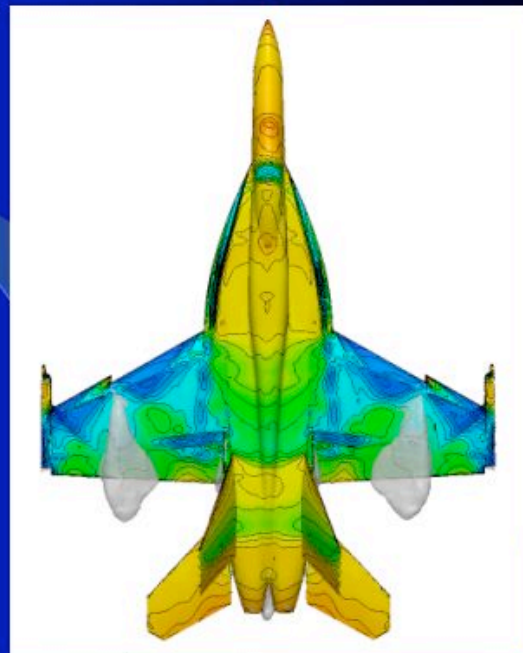
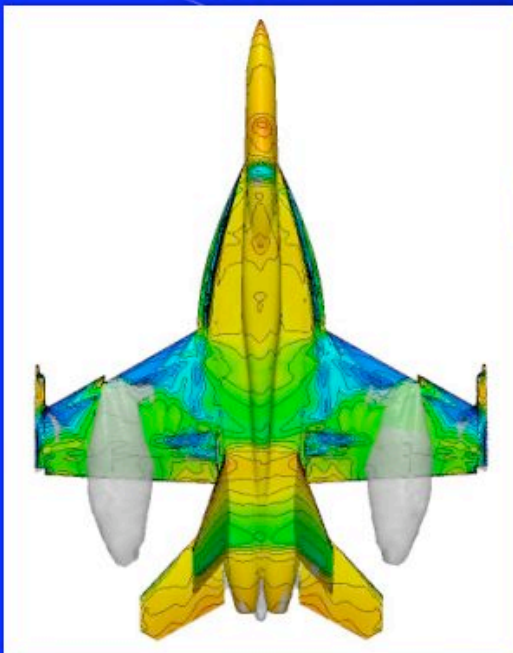




Run 240 ( $\theta \approx 8.5^\circ$ ),  $\phi \approx 10^\circ$

SST

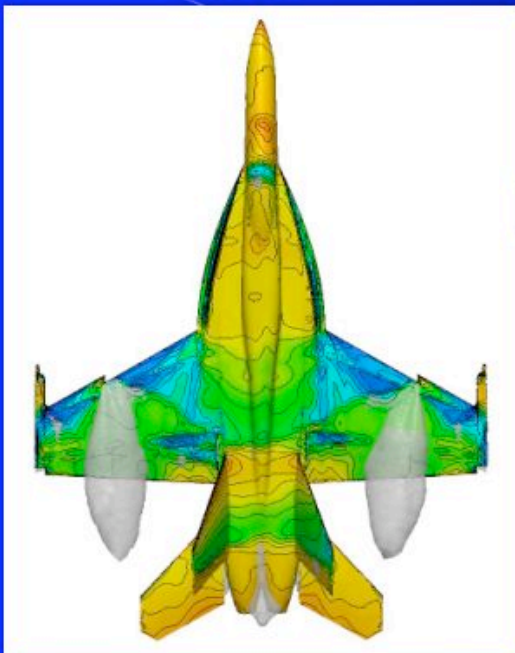
DES



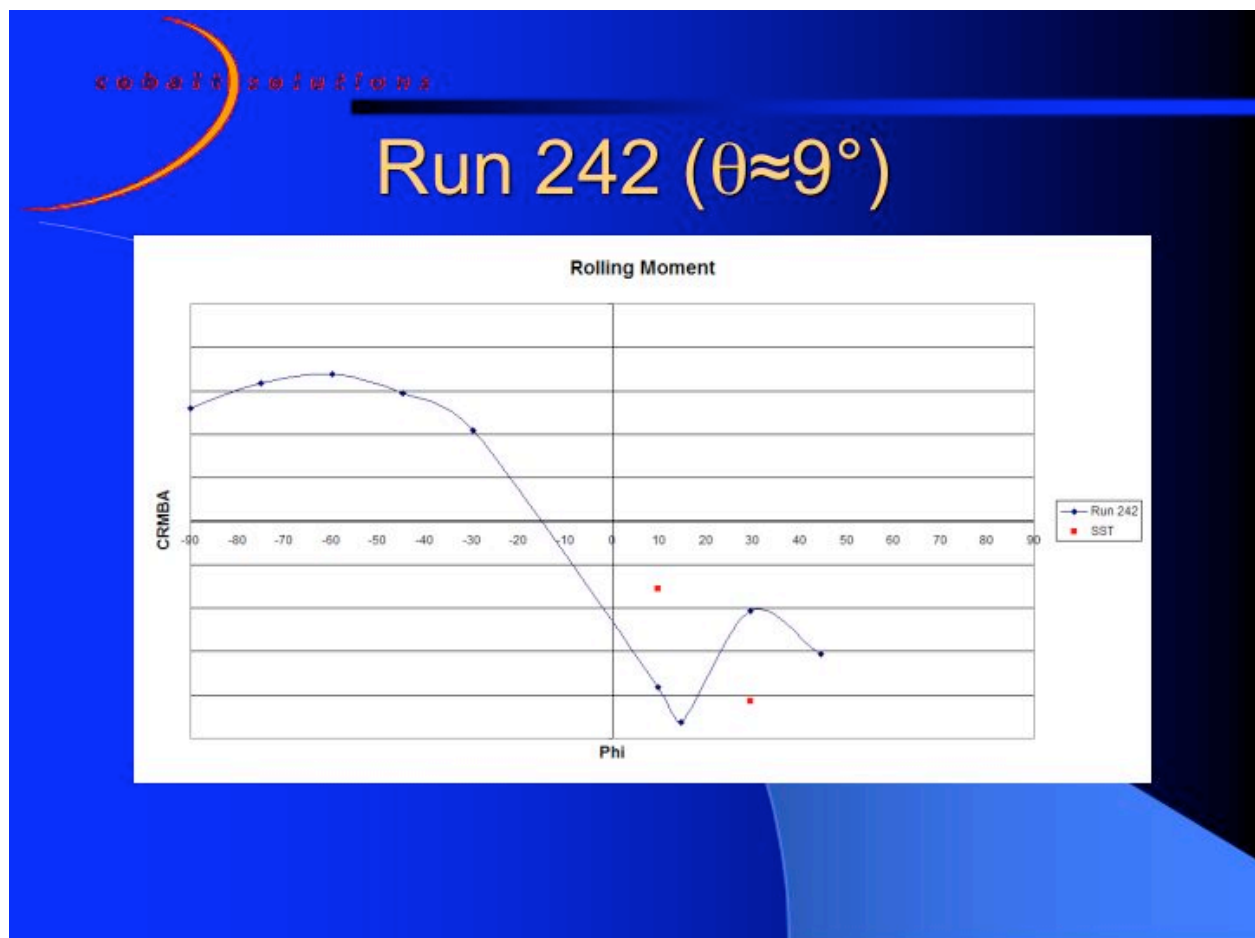
coherent solutions

Isosurface of  $u=0$ , surface colored by pressure

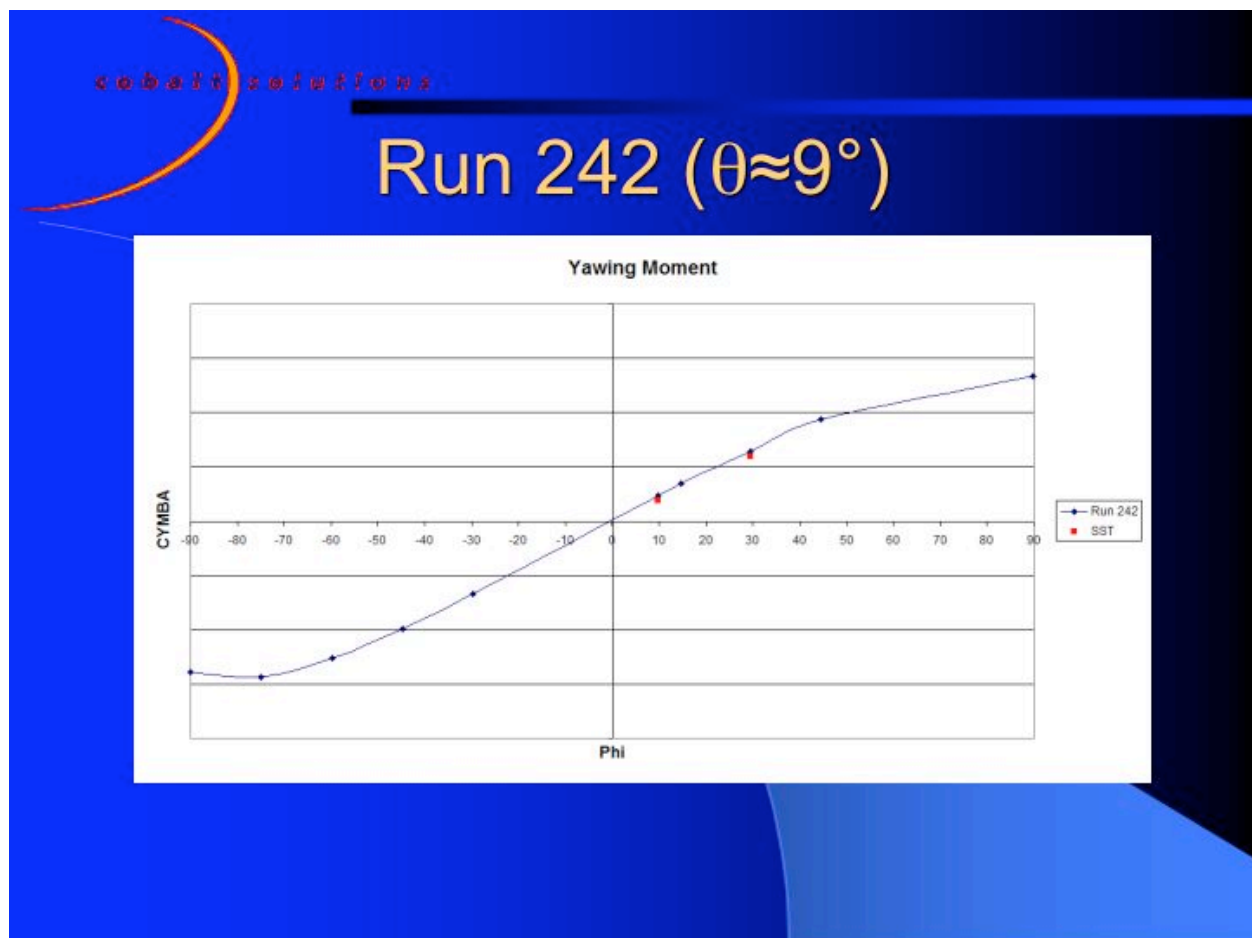
Run 240 ( $\theta \approx 8.5^\circ$ ),  $\phi \approx 30^\circ$   
SST



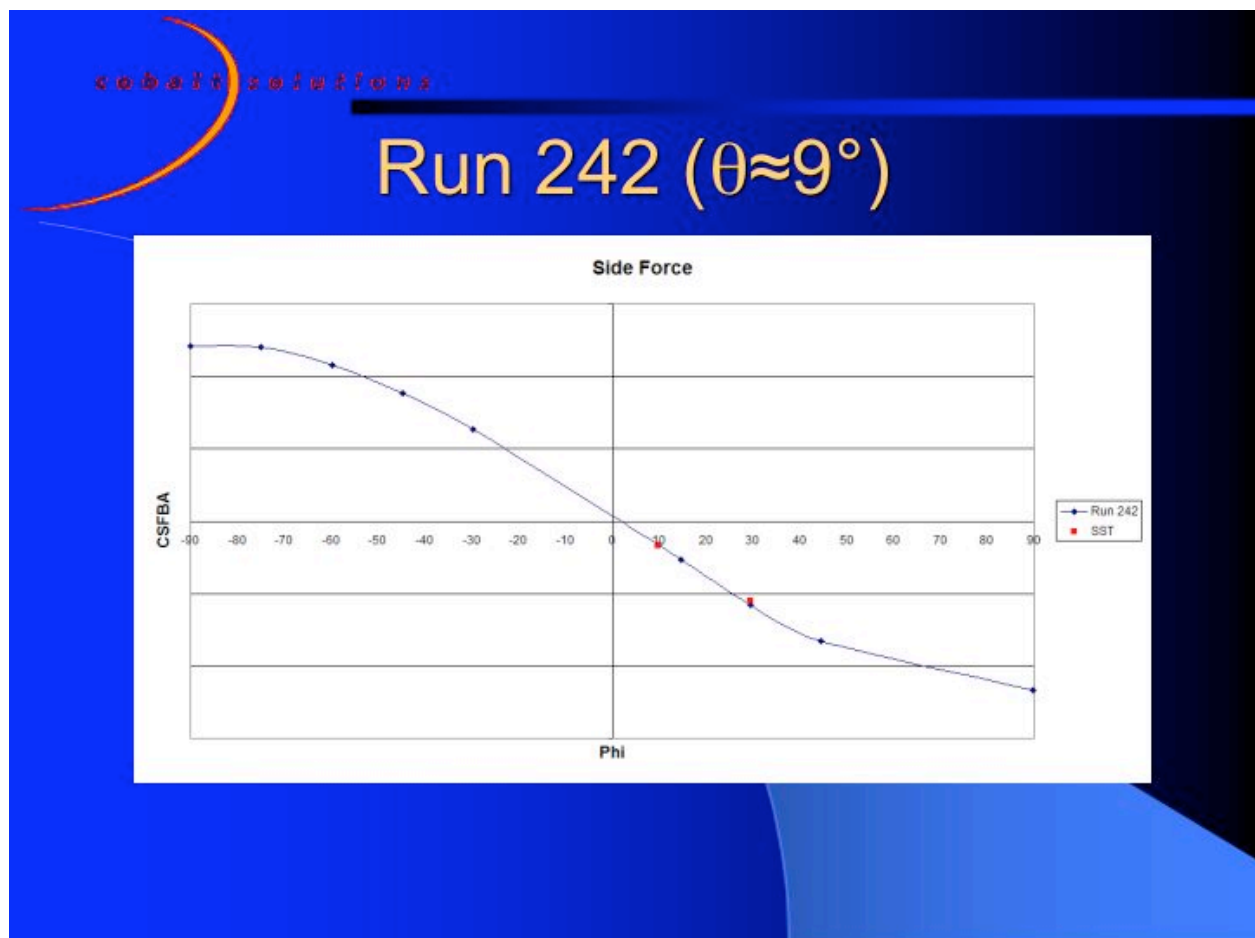
Large asymmetries in wind tunnel data. Around this angle there was difficulty in testing, since model dynamics became significant.



Good agreement for yawing moment, as with all cases.



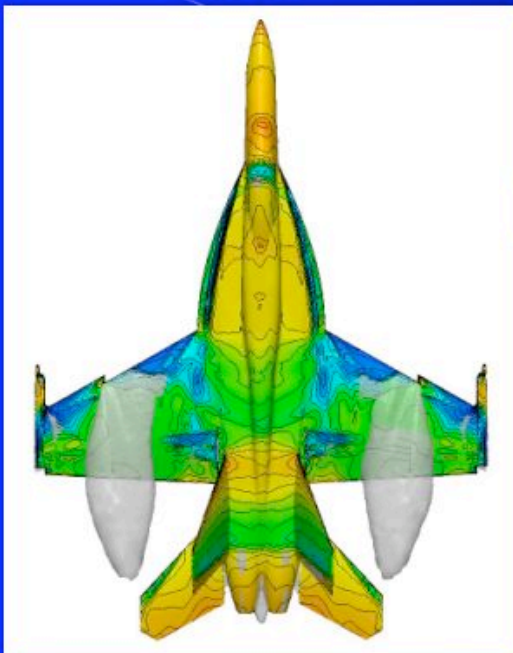
Good agreement for side force, as with all cases.



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Isosurface of  $u=0$ , surface colored by pressure

Run 242 ( $\theta \approx 9^\circ$ ),  $\phi \approx 10^\circ$   
SST

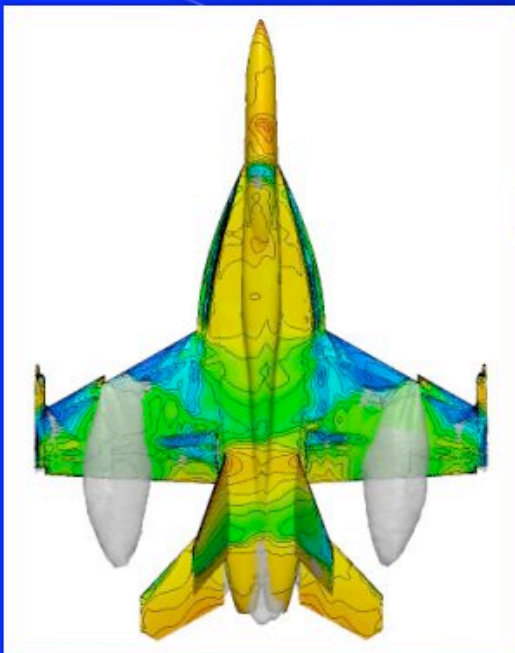




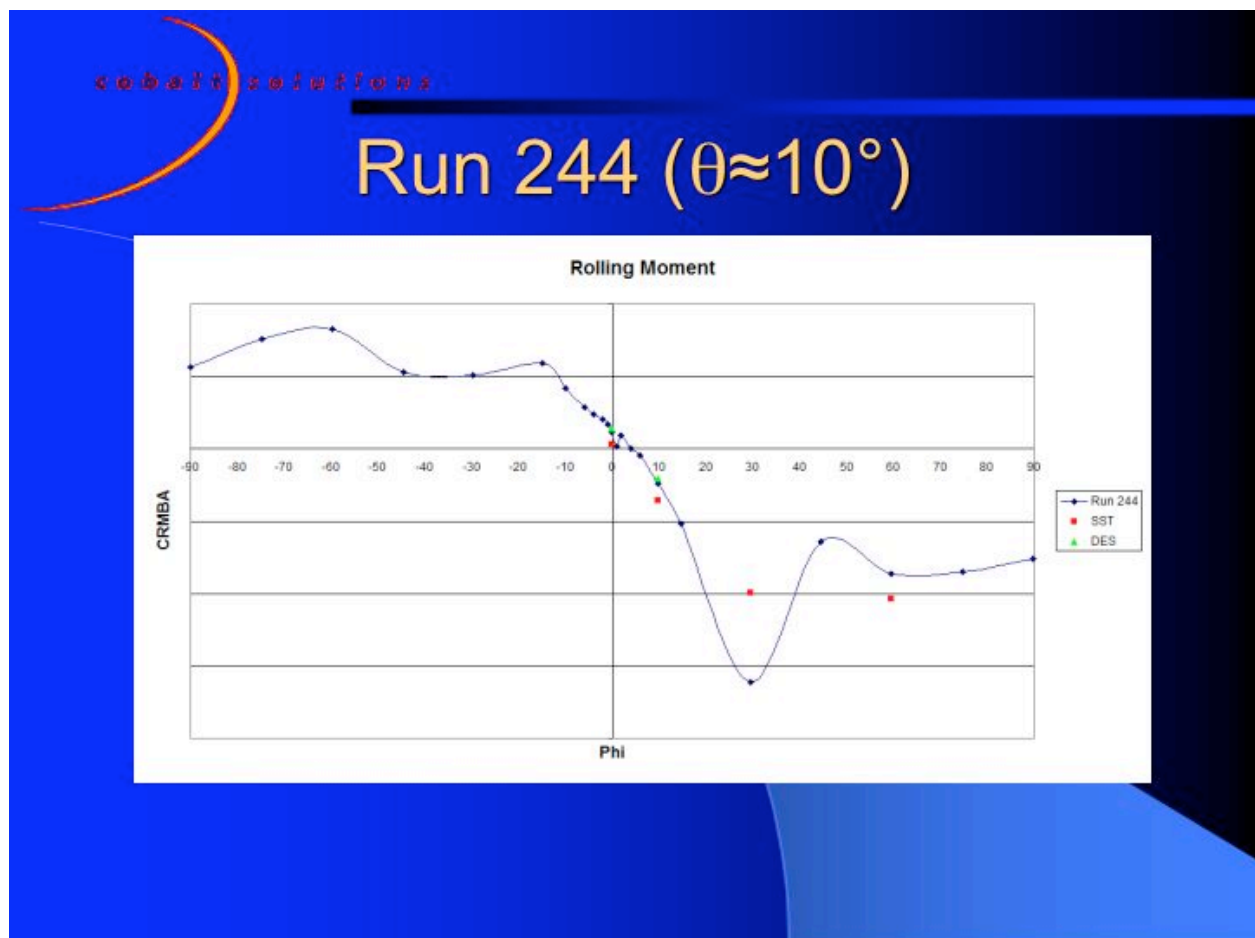
ceba solutions

Isosurface of  $u=0$ , surface colored by pressure

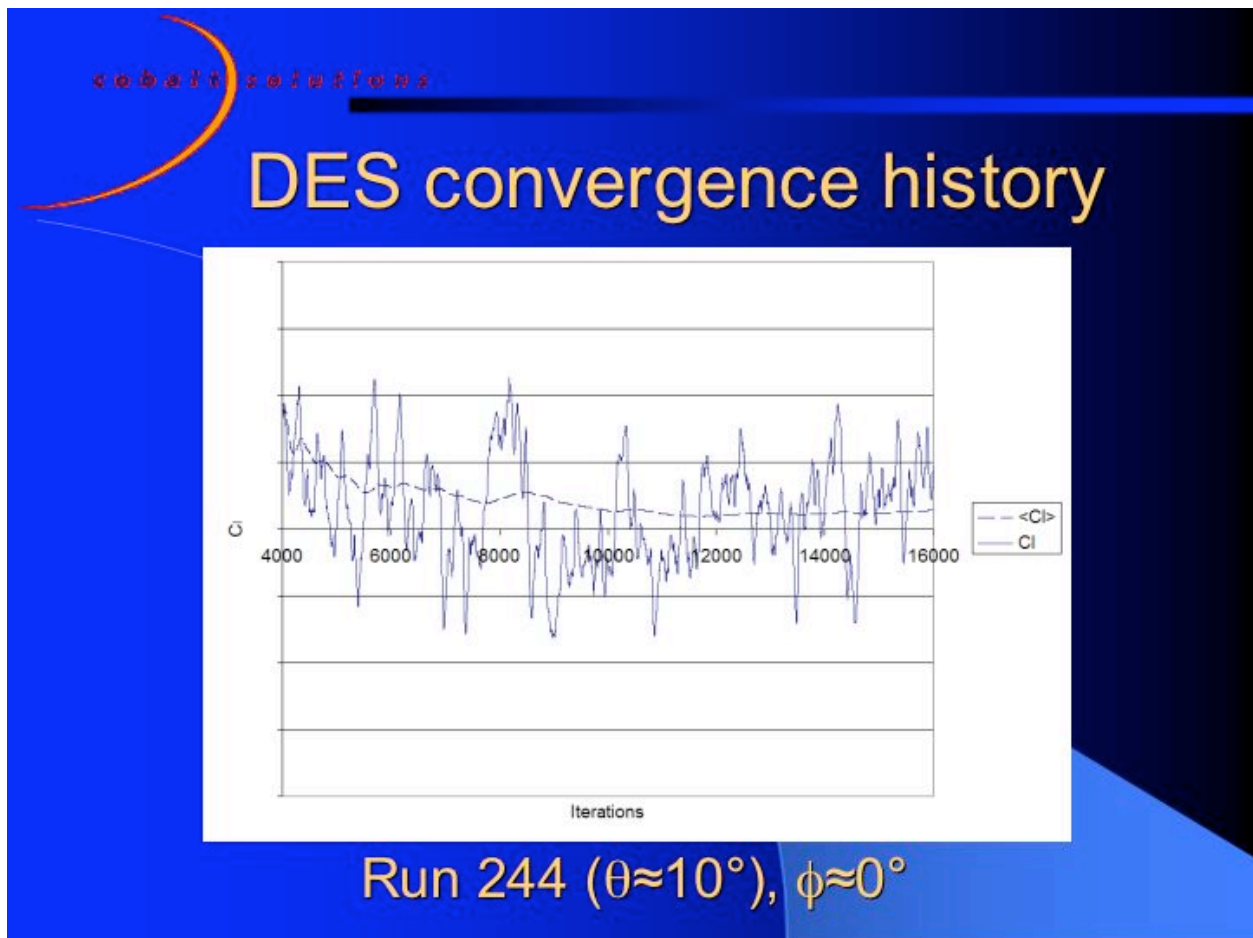
Run 242 ( $\theta \approx 9^\circ$ ),  $\phi \approx 30^\circ$   
SST



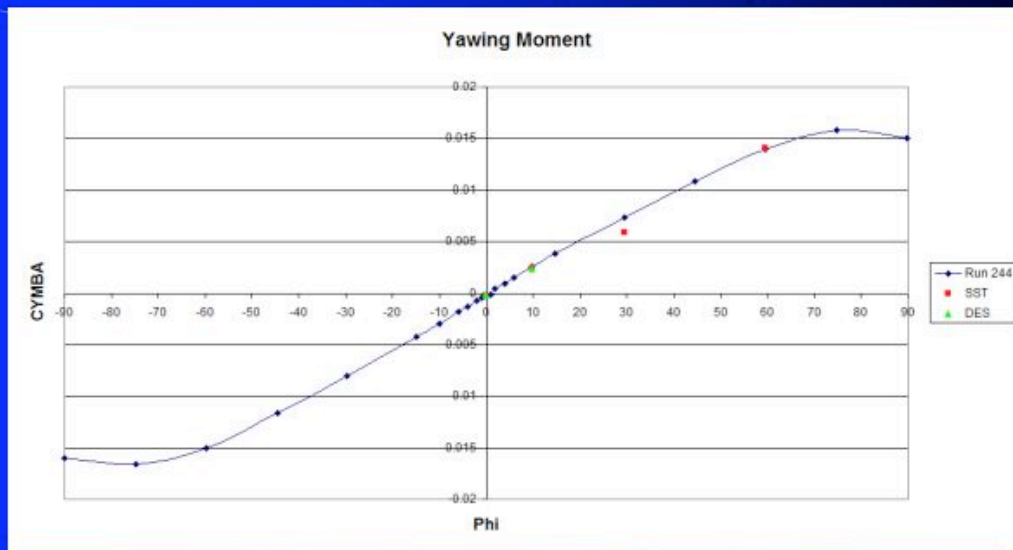
Rolling moment offset predicted by DES – is the sample size large enough?



Looks like enough samples have been taken to well define rolling moment. However more might change the time-averaged rolling moment some.



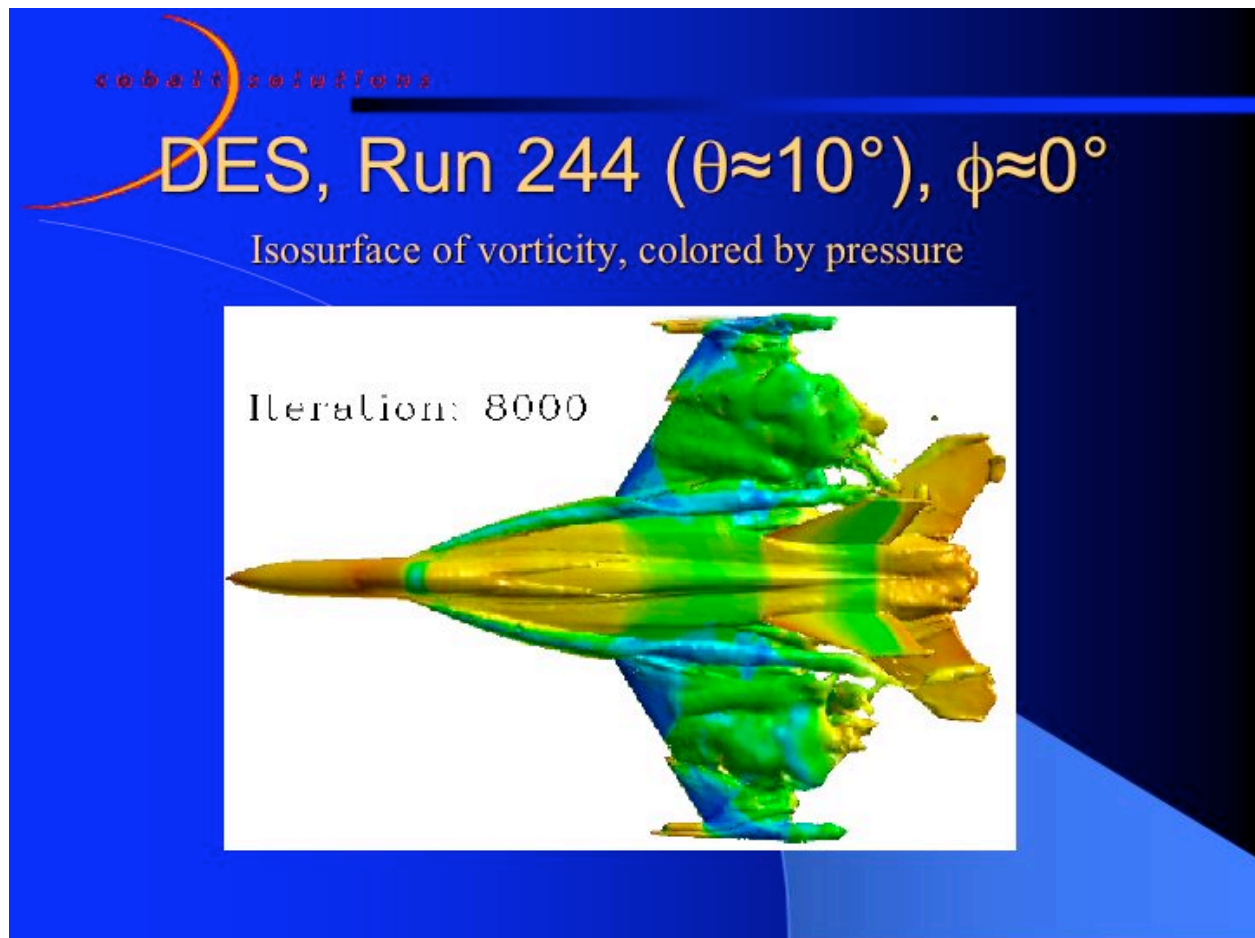
# Run 244 ( $\theta \approx 10^\circ$ )



# Run 244 ( $\theta \approx 10^\circ$ )



Unsteadiness now is due to separation moving from leading to trailing edge of the leading edge flap.

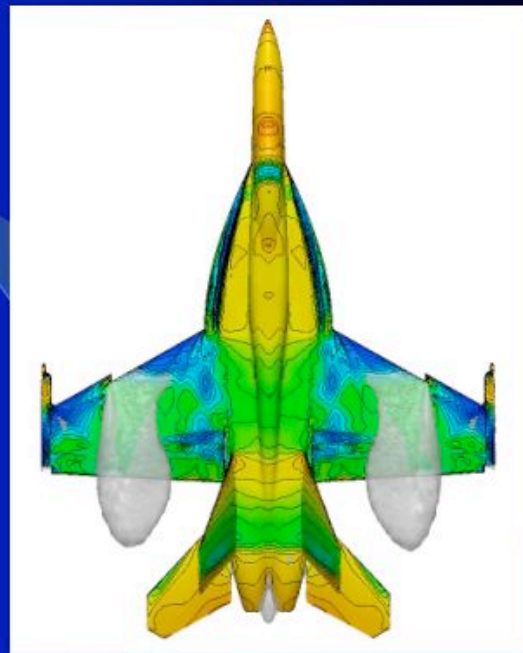
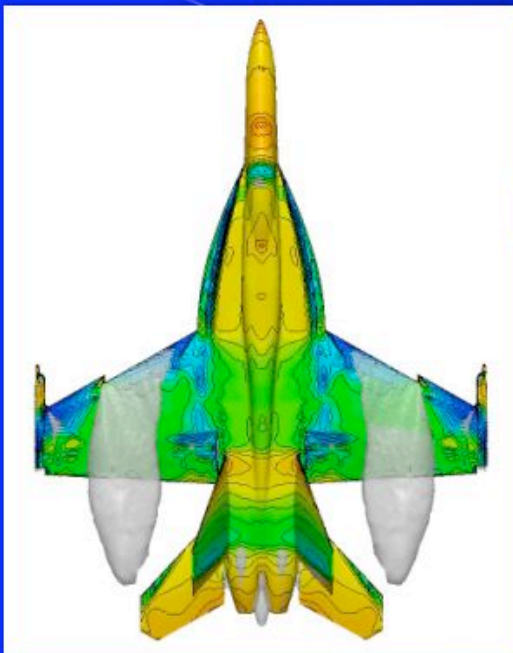




Run 244 ( $\theta \approx 10^\circ$ ),  $\phi \approx 0^\circ$

SST

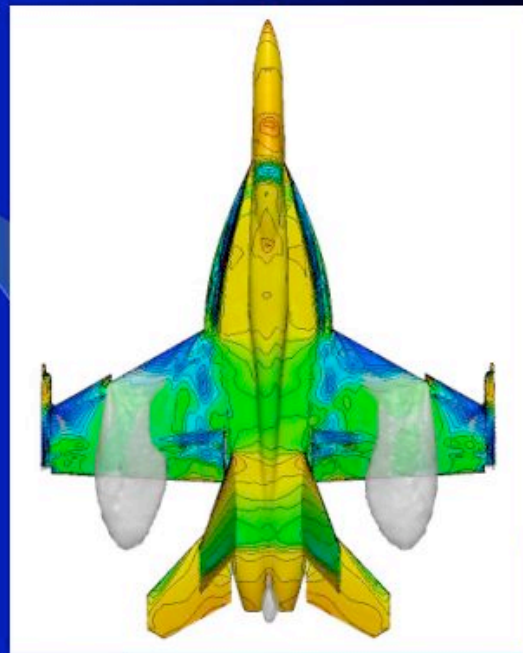
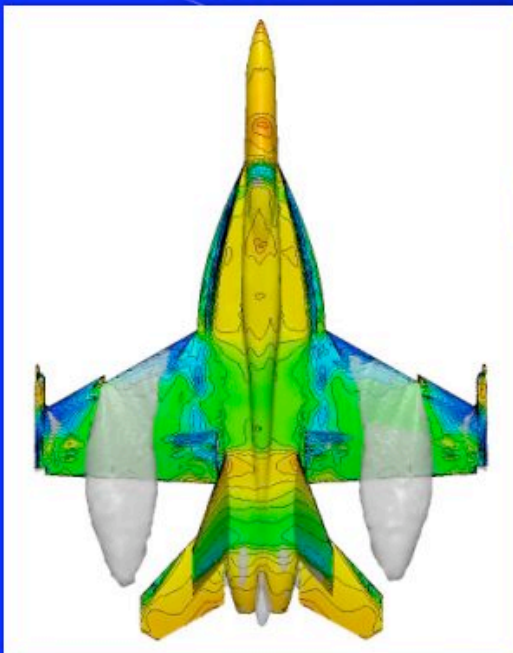
DES



Run 244 ( $\theta \approx 10^\circ$ ),  $\phi \approx 10^\circ$

SST

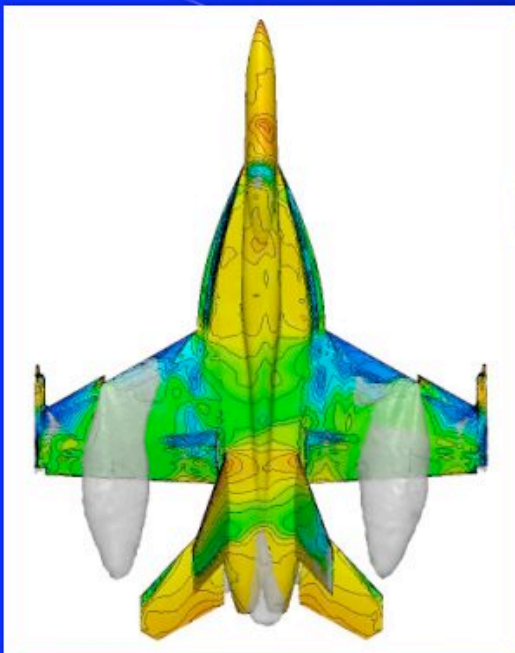
DES



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Isosurface of  $u=0$ , surface colored by pressure

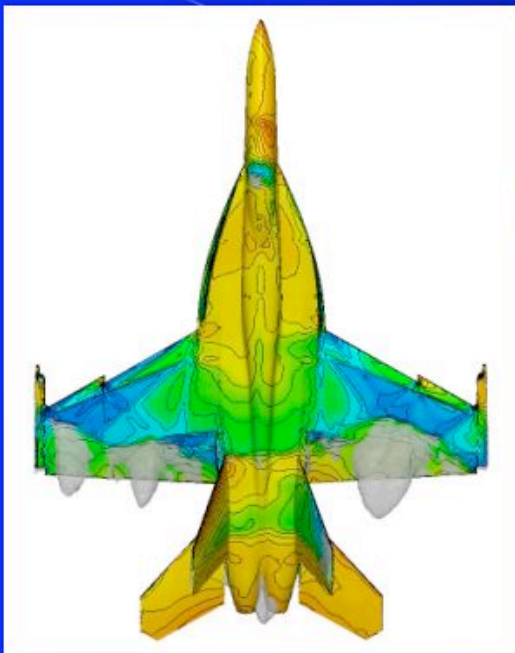
Run 244 ( $\theta \approx 10^\circ$ ),  $\phi \approx 30^\circ$   
SST



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Isosurface of  $u=0$ , surface colored by pressure

Run 244 ( $\theta \approx 10^\circ$ ),  $\phi \approx 60^\circ$   
SST



# Oscillating Cases

ALE = Arbitrary Eulerian/Lagrangian.



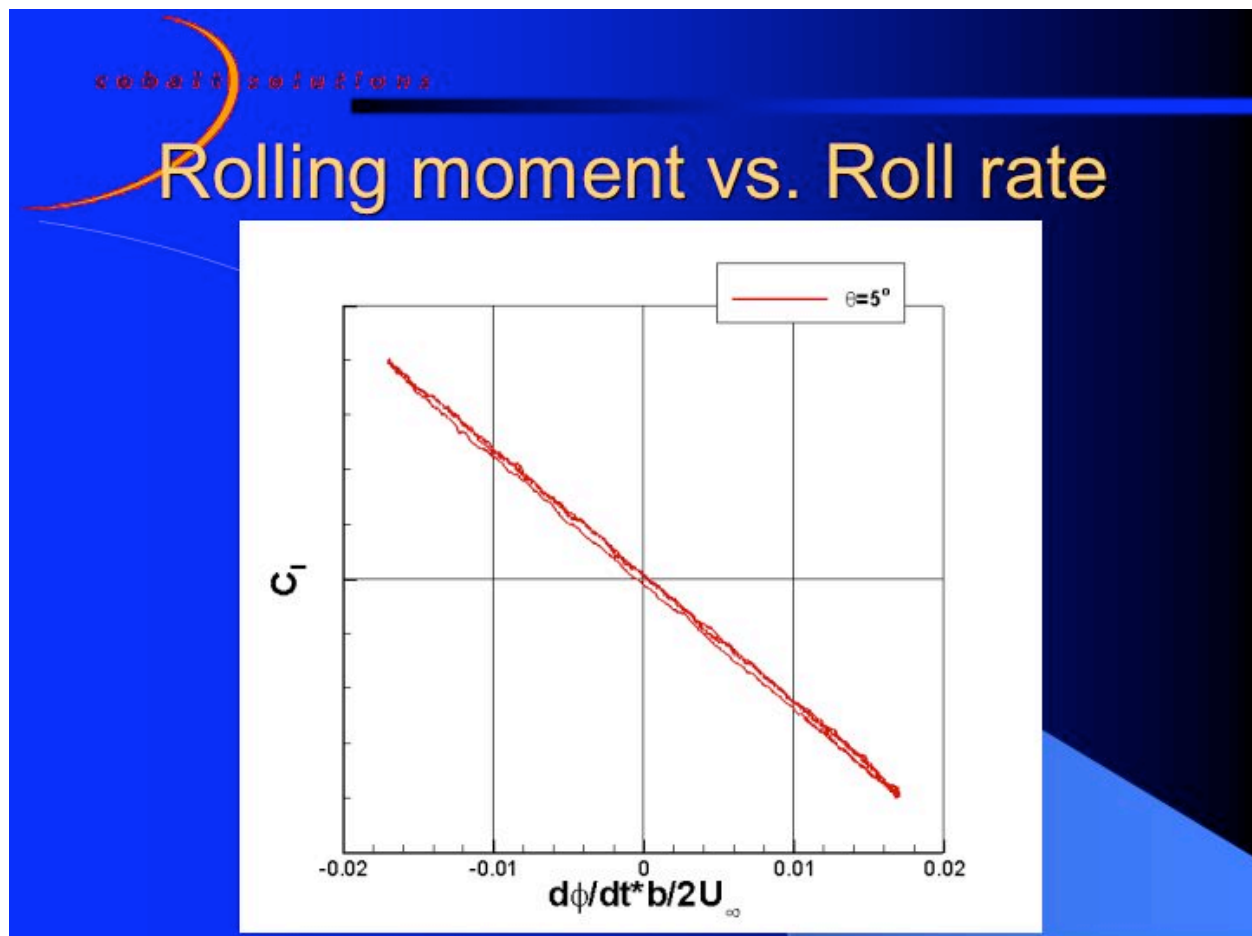
## Solution Procedure

- Time-accurate with ALE formulation for grid motion
  - 5 Newton sub-iteration (for accurate grid motion)
  - $\Delta t^*=0.02$  (ran several timesteps to demonstrate timestep convergence)
- Prescribed sinusoidal oscillation around longitudinal axis
  - $\tan^{-1}(f^*)=1^\circ$ ,  $f^*=0.0174$
  - 2,600 iterations per cycle
  - 4,000 cpu-hours per cycle
  - $\pm 5^\circ$  oscillation
- Menter's SST RANS model

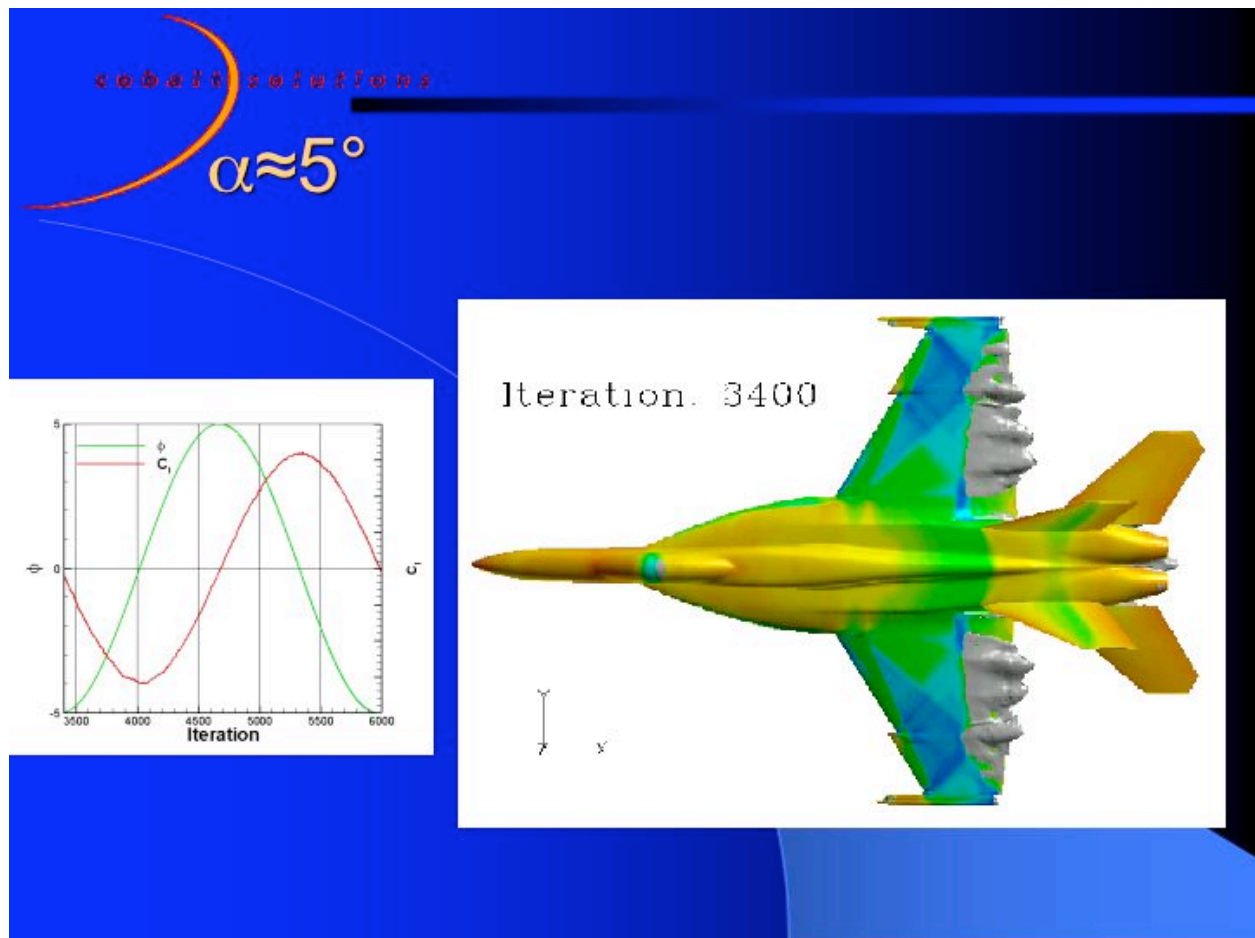
$$\tan^{-1}\left(\frac{fb}{2U_\infty}\right) = \tan^{-1}(f^*) = 1^\circ$$



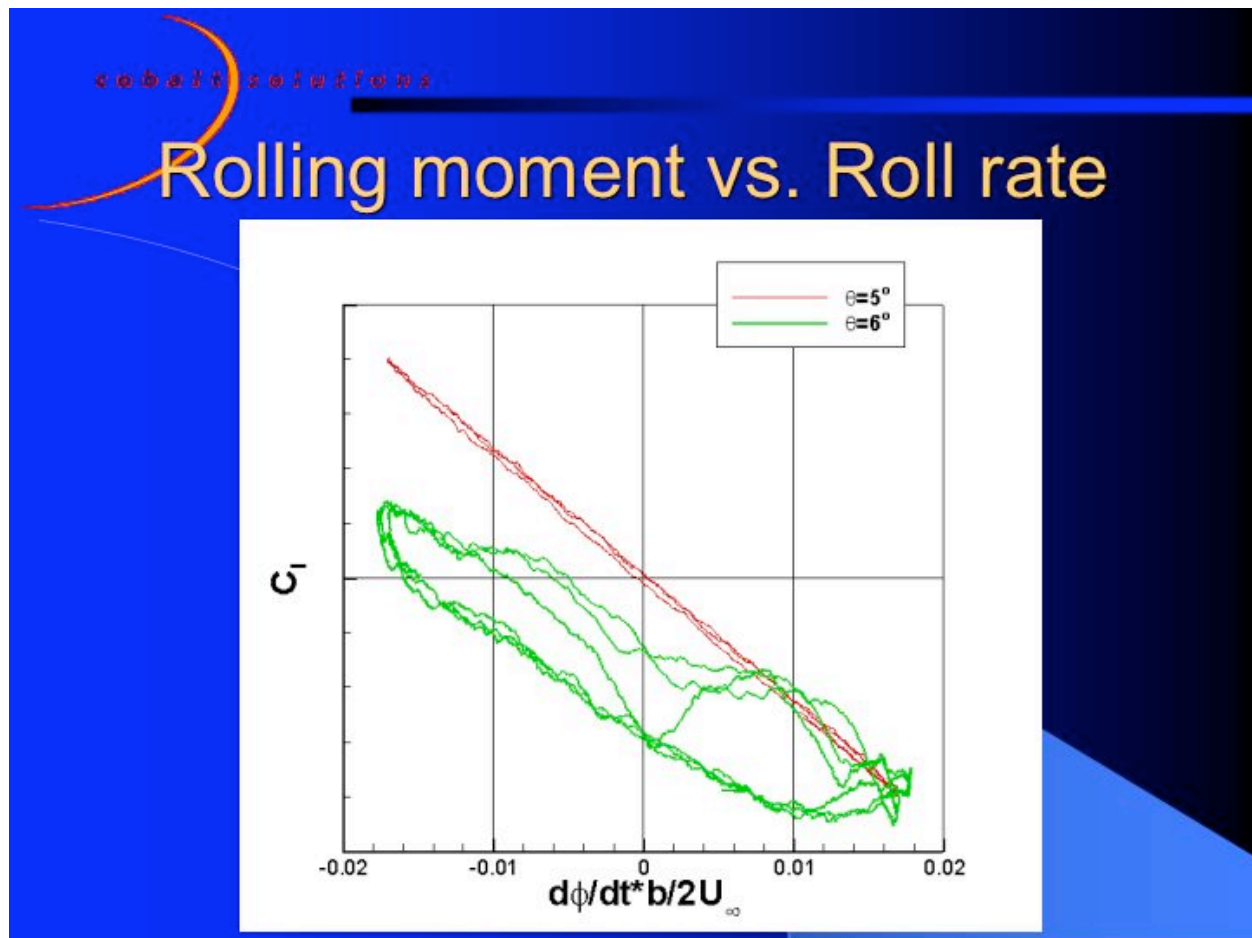
Linear and well behaved. Stable roll damping.



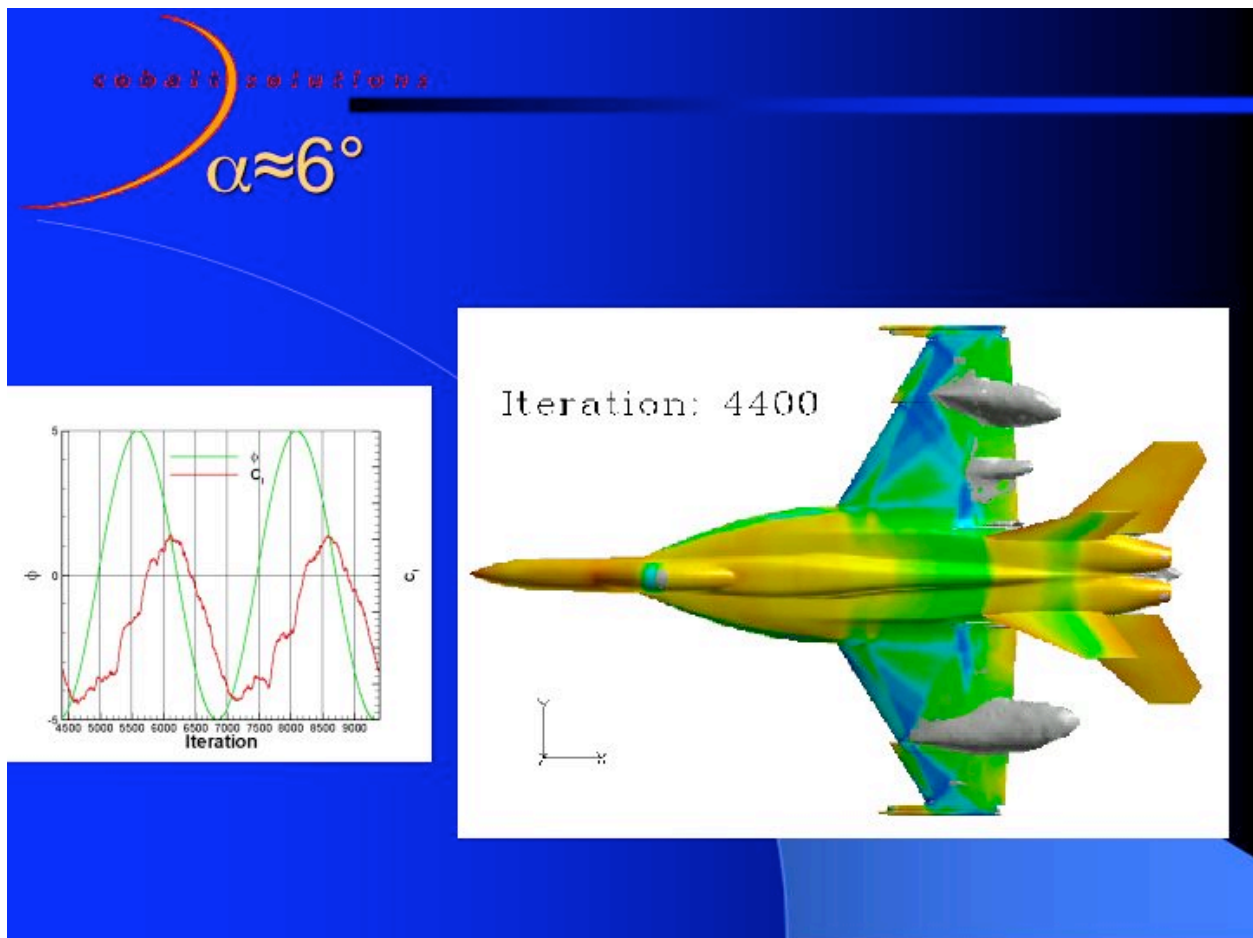
Separation at trailing edge – flow well behaved.



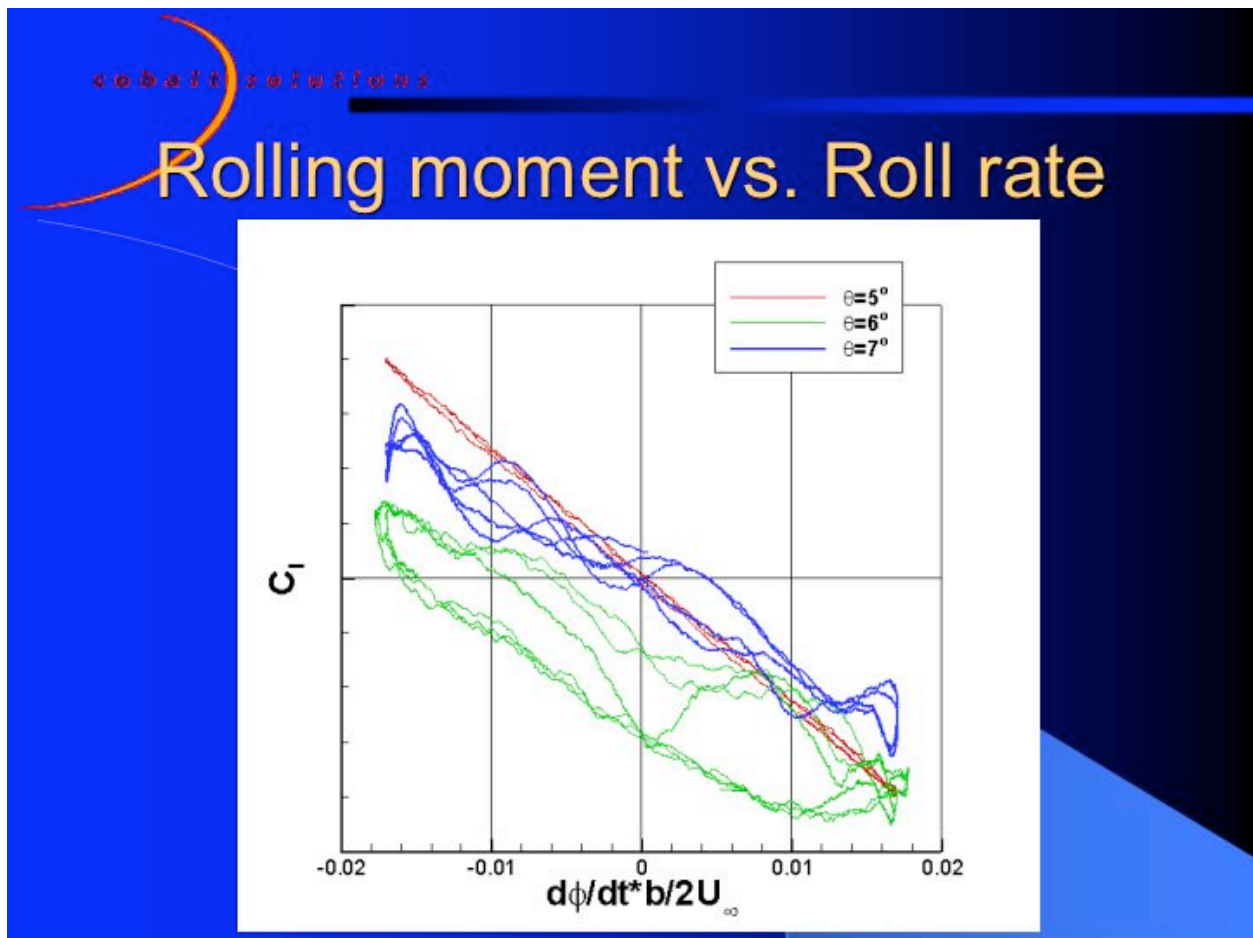
Large rolling moment offset. Several cycles run with varied timestep, but offset remained.



Offset due to differences in separation location. Hysteresis?

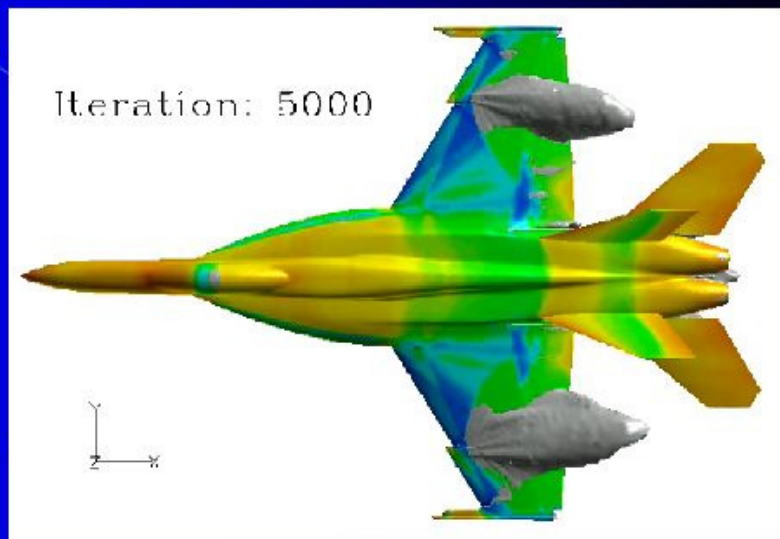
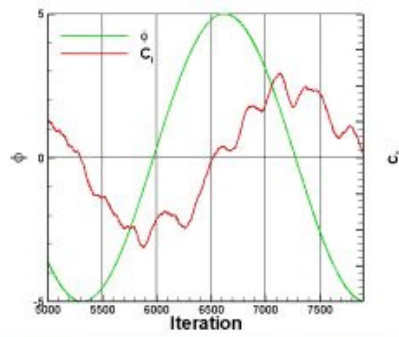


Slightly chaotic behavior, but linear and stable roll damping.

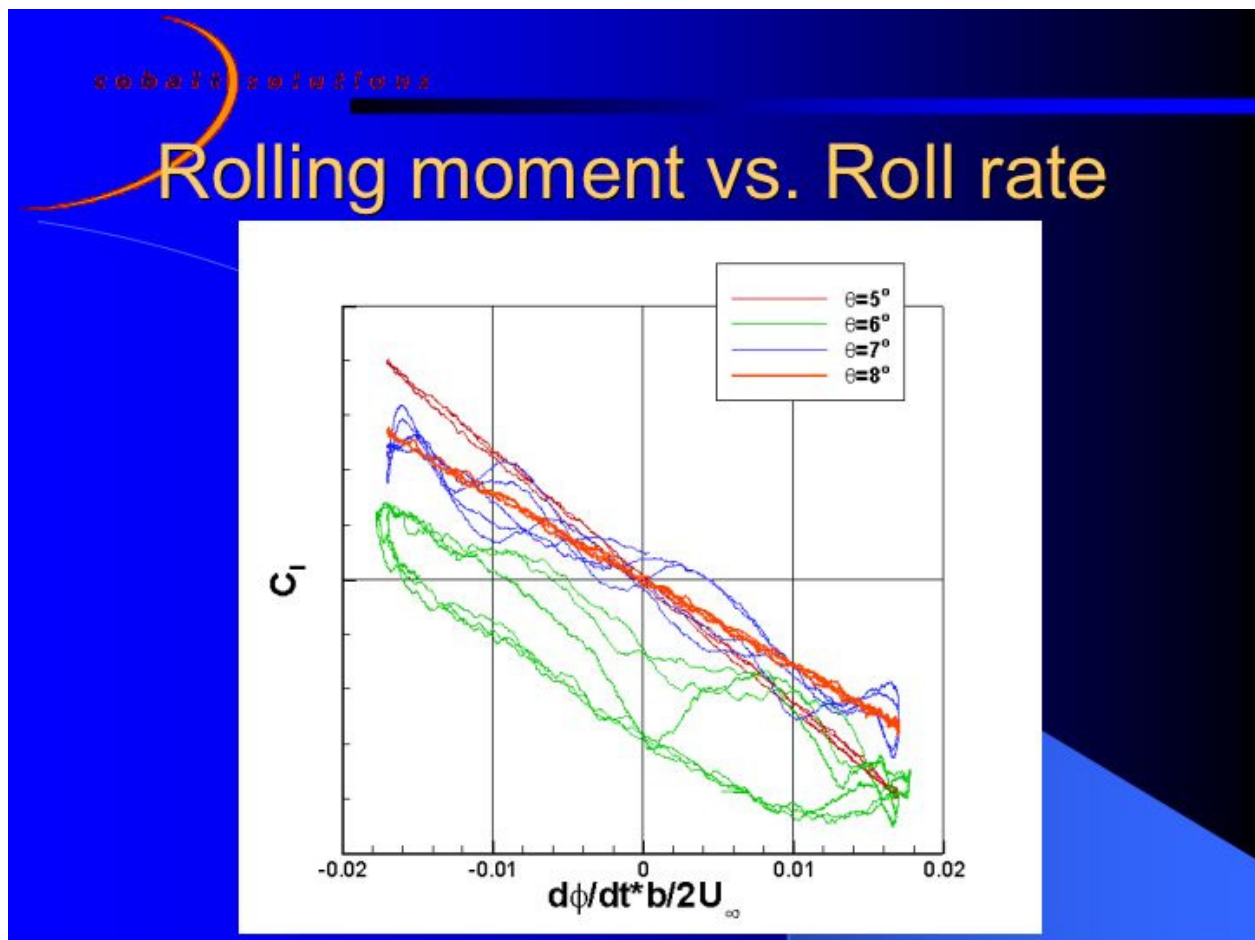


convergence

$$\alpha \approx 7^\circ$$

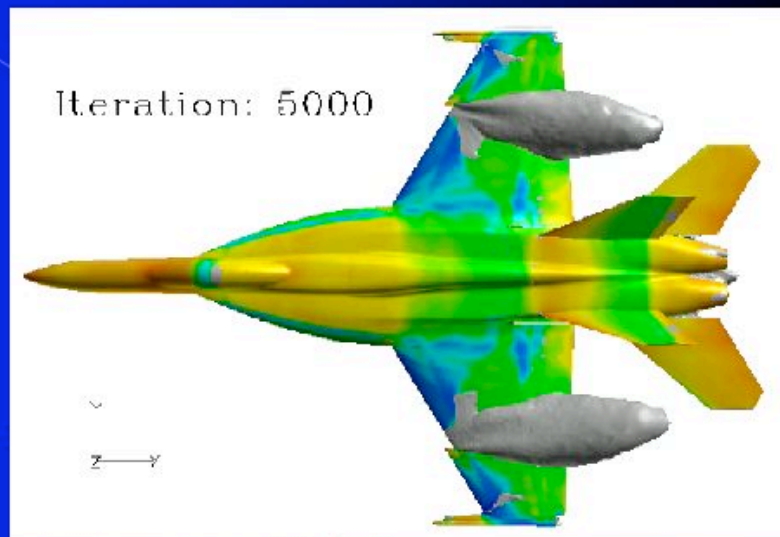
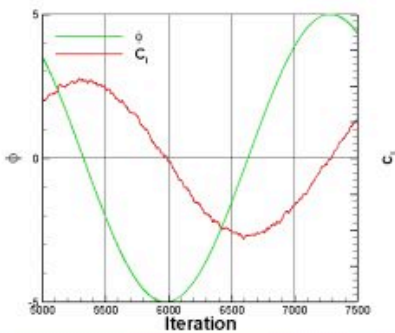


Positive roll damping. Note lowered slope – due to lower lift curve slope once shock moves forward on the wing.



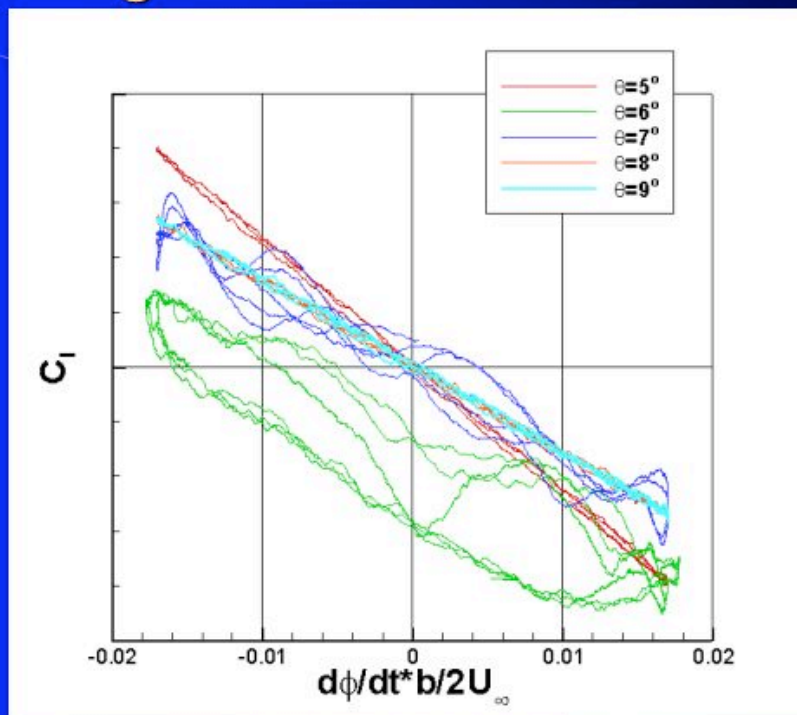
coherent solutions

$$\alpha \approx 8^\circ$$

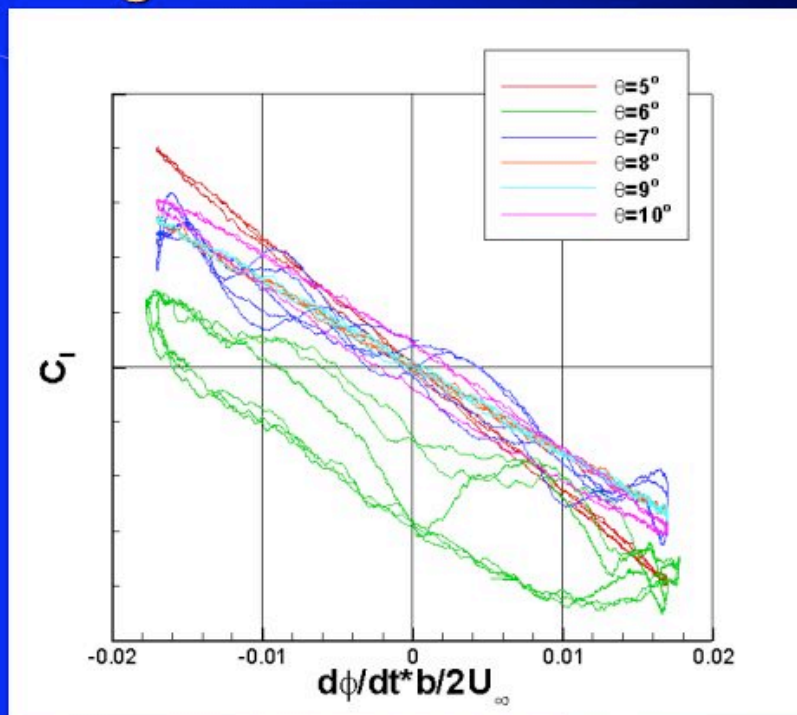




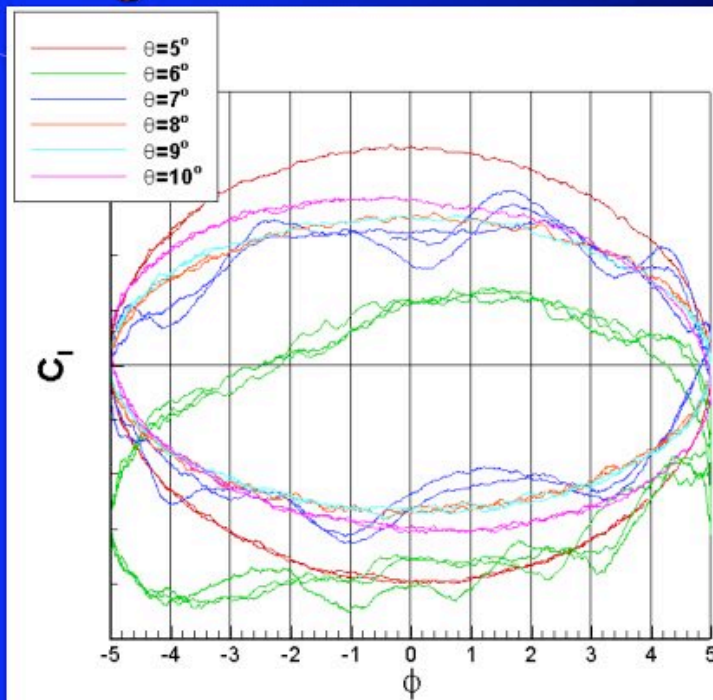
# Rolling moment vs. Roll rate



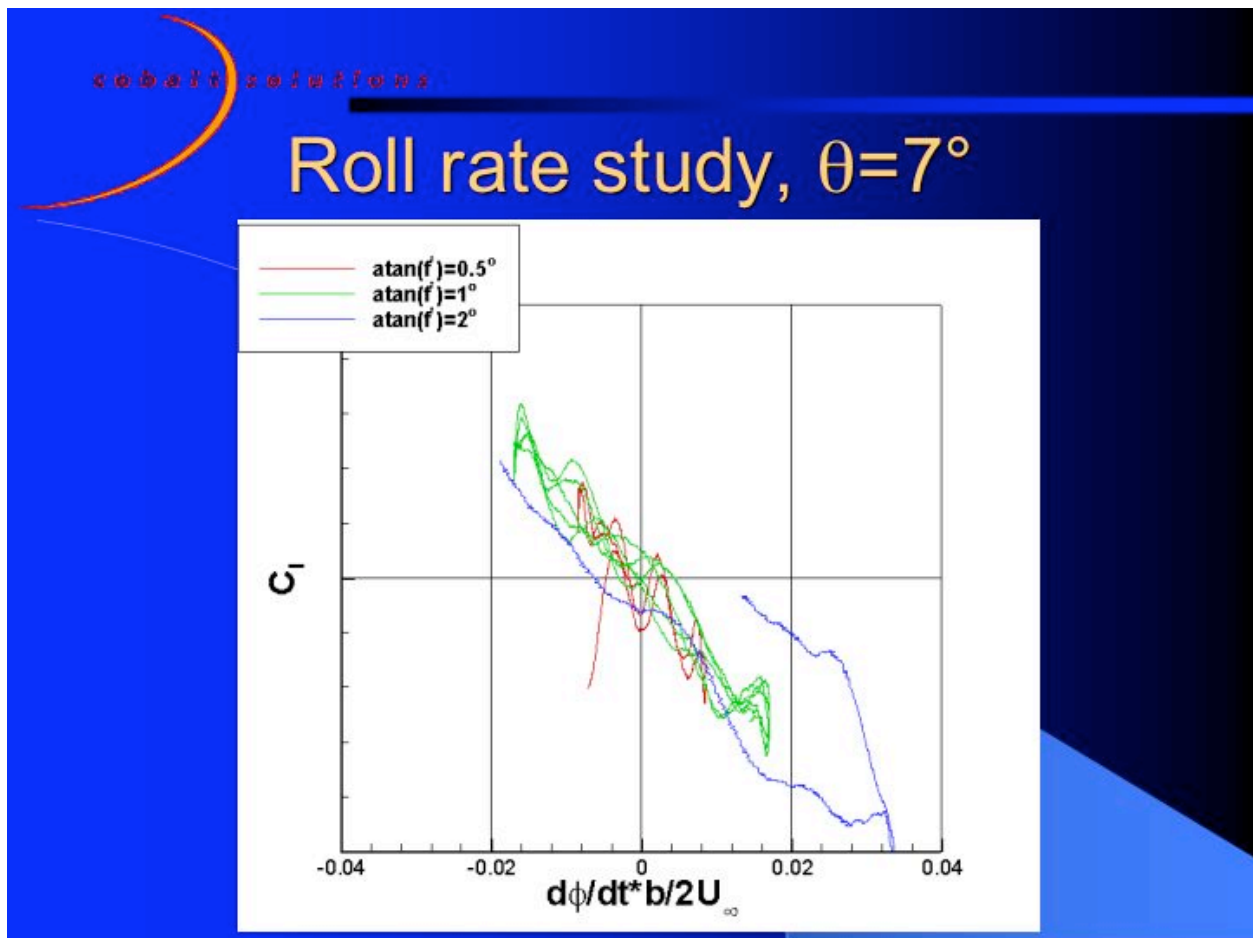
# Rolling moment vs. Roll rate



## Rolling Moment vs. Roll angle



Study still underway – not enough samples. Looking at dependence of roll damping on roll rate.



## Conclusions

- RANS and DES applied to predict static stability derivatives in roll in AWS regime
  - DES showed better lift and moment predictions
  - Yawing moments and side force well predicted by both methods
  - Rolling moment more sensitive (both for CFD and wind tunnel)
- Prescribed rolls used to look at roll damping (RANS only)
  - All cases were stable in roll, but in AWS regime had more chaotic behavior. For one angle there was a significant rolling moment offset
  - Comparison to experiments still ongoing
- Continuing work
  - DES of prescribed rolls
  - More iterations on varying roll rate